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BBN Laboratories Incorporated

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Report No. 6509

OCS Study
MMS87-0084

Prediction of Drilling Site-Specific Interaction of Industrial Acoustic Stimuli and Endangered Whales in The Alaskan Beaufort Sea

FINAL REPORT

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PREDICTION OF DRILLING SITE-SPECIFIC INTERACTION OF INDUSTRIAL ACOUSTIC STIMULI AND ENDANGERED WHALES IN THE ALASKAN BEAUFORT SEA

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ABSTRACT

The underwater acoustic environment and sound propagation characteristics associated with six offshore oil drilling sites in the Alaskan Beaufort Sea were measured during the mid-August to mid-September 1985 and 1986 periods. Analysis of the field data has resulted in a compilation of ambient noise statistics, noise signatures of sources of sound associated with oil industry activities at those sites, and a quantitative ability to predict noise levels from oil industry activities as a function of distance from the sound source. Results of previous research regarding behavioral responses of bowhead whales (Balaena mysticetus) and gray whales (Eschrichtius robustus) to acoustic stimuli have been used in this study as well. The synthesis of the new acoustic data with prior information regarding whale behavioral response to underwater sound has permitted the derivation of site-specific estimates of zones of influence relating whale response to industrial noise. The results of this two year effort are provided in this report.

The sound propagation findings indicate that sound attenuates less rapidly with increasing distance in the Beaufort Sea than in many other areas, i.e., there is very efficient cylindrical spreading (10 log Range) of acoustic energy to ranges of 25 to 40 km from the Alaskan Beaufort sites studied. Two acoustic criteria have been used in relating industrial noise levels to whale behavioral response: (1) predicted signal-to-noise ratio (S:N) in the 1/3-octave band of highest S:N, and (2) absolute received sound pressure level in either that same 1/3-octave band or in the overall effective bandwidth of the signal. Since it is not known whether S:N or absolute noise level is more important in eliciting responses by bowhead and gray whales, both have been considered in developing behavioral response predictions.

Site-specific zones of potential responsiveness of bowhead whales around to six continuous sources of industrial noise have been estimated. For instance, assuming that the threshold of responsiveness for some bowheads is an industrial noise to ambient noise ratio of 20 dB, the radii of response for two of the more intense continuous sounds are estimated to extend 6 to 34 km from two tugs holding a barge against a gravel island (bollard condition) and 5 to 12 km from a drillship drilling, depending on site. For the quietest source, drilling on an artificial island, the predicted radii of potential response vary from 0.05 to 1.8 km. A minority of the bowhead whales are expected to respond when the S:N = 20 dB; a few whales may respond somewhat further away.

Roughly half of bowheads are expected to respond (approximate avoidance probability of 0.5) when the S:N is 30 dB. At the sites investigated, 30 dB S:N conditions are expected to occur 1.6 to 12 km from the two tugs in bollard condition, 1 to 4 km from the drillship drilling and 0.02 to 0.2 km from drilling on an artificial island. Based on the absolute level criterion, for which the approximate threshold is 110 dB re 1 μPa, expected zones of responsiveness of roughly half of the bowhead whales are of the same order as for the 30 dB S:N condition.

For gray whales, the estimated radii of responsiveness to drillship operations vary from 4.8 to 9.6 km based on a received level of 110 dB re 1 μPa in the dominant frequency band, which is the level resulting in a 0.1 probability of avoidance (Pa). For 120 dB absolute level and a P_a of 0.5, the estimated zones of responsiveness around the drillship vary from 1.4 to 3.3 km, depending on site.

The zones of audibility, within which the industrial noise level equals or exceeds the ambient level (S:N = O dB), will be much larger than the zones of responsiveness. Under median ambient conditions they are predicted to vary from 21 km to greater than 50 km, depending on site, for the sources noted above. These values will depend strongly on ambient noise conditions. Behavioral changes in the outer portion of the zone of audibility beyond the zone of responsiveness, are expected to be subtle at most.

A second important category of industrial noise, that which is intermittent or is fluctuating significantly in level, has also been considered. Icebreakers working on ice at drillsites, dredge operations and short-term operations of a tug towing a loaded barge are examples. Since we do not have specific data on responses of whales to this type of source, the zones of responsiveness have been estimated in two ways: (1) assuming that they respond similarly to man by reacting to an average of the fluctuating acoustic energy over a finite period of time, and (2) assuming that the whales respond to the highest short term signal level in the same way as they do to continuous noise. The peak levels of sound radiated by a working icebreaker are the most intense of the intermittent sounds that were considered. For that source, the zones of responsiveness (30 dB S:N and 110 dB absolute level criteria) vary from 4.6 to 12 km for the first assumption and from 19 to 34 km based on the second assumption. Given the widely varying predictions and their dependence on the assumptions about responsiveness, the issue of whale responsiveness to varying industrial noises should be studied further,

ACKNOWLEDGEMENTS

The research represented by this report was performed for and with support from the Alaska OCS Office of the U.S. Department of the Interior, Minerals Management Service, in Anchorage, Alaska. The support and interest in all aspects of the project provided by Dr. Jerome Montague, Contracting Officer's Technical Representative, of that office are particularly appreciated. The following groups and individuals were also very important to the completion of this project.

The cooperation extended to BBN by the operators at the sites visited in the Alaskan Beaufort Sea was very important: Shell Western (Sandpiper and Corona), Unocal (Hammerhead), Exxon (Orion), and Amoco (Sandpiper, Erik, and Belcher) all provided helpful assistance during the field measurement portion of the project.

Dr. Charles Greene of Greeneridge Sciences, Inc., provided BBN with copies of selected portions of magnetic tape recordings that he acquired at Hammerhead and Sandpiper during the 1985 field season. The availability of those data, the release of which was approved by Unocal, Shell Western and LGL, was particularly important since heavy ice conditions during the BBN field measurement period prevented BBN from acquiring the needed data. Dr. Greene also contributed historical acoustic data from measurements in the Canadian Beaufort, including some unpublished data, which were reworked by LGL to provide additional 1/3 octave band information. During 1986 he coordinated and provided a Corona drillship activity log for the dates and times during which BBN was making field measurements.

The availability on short notice of the research vessels M.V. JUDY ANN in 1985, through Oceanic Research Services, Inc., and the M.V. ARCTIC ROSE in 1986, through Beaufort Transportation, Inc., was essential to the success of the field measurement efforts. The contributions and skills of Mr. Geoffrey Orth and Mr. Richard Schuerger of the JUDY ANN and Mr. James Adams and his crew of the ARCTIC ROSE, particularly during difficult ice and weather conditions, assured the acquisition of the needed field data.

Western Geophysical Inc. and Shell provided important information regarding their seismic survey operations in the Alaskan Beaufort in 1986. Data relating to survey runs of WESTERN POLARIS with its air gun array system during BBN field measurement periods permitted the computation of waterborne acoustic transmission loss to distances beyond the capability of the BBN sound projector system. Their willing cooperation and contributions to the project have been very useful.

The NOAA-Anchorage office of the National Oceanic and Atmospheric Administration (Mr. Erdogan Ozturgut) provided what proved to be very important information regarding profiles of ocean salinity and temperature as determined from icebreaker POLAR STAR in early to mid-October 1986. Their assistance was critical in establishing boundaries on estimates of zones of influence on endangered whales.

At LGL Ltd., environmental research associates, Ms. M.A. McLaren assisted Dr. Richardson in compiling data on whale response. Her help is greatly appreciated. Dr. Rolph Davis provided important editorial assistance during preparation of both the interim report and this final report.

The following BBN staff members assisted the authors in several important ways in contributing to the success of the field portion of this project. Their enthusiasm and dedication were essential to the performance of that work:

Mr. Bart Burkewitz: Field measurements and data analysis (1986)

Mr. Jeffrey Doughty: Field measurements (1985)

Mr. Arthur Margerison: Field measurements (1985)

Dr. Daniel L. Nelson: Field measurements (1985)

Mr. Arch Owen: Field measurements and data analysis (1986)

Mr. George Shepard: Field measurements, 1985-86, and data analysis (1985) and co-author of the interim report.

Dr. Preston W. Smith, Jr., provided important assistance in application of the Weston shallow water acoustic transmission loss model to Beaufort Sea conditions. The word processing talents and patience demonstrated by Ms. Judy Russo in the preparation of the manuscript of this report are especially appreciated.

Dr. Christopher Clark and Dr. Peter Tyack provided consulting services during the planning process for this project and reviewed the results of the first phase (1985) of the study. Mr. James Bird provided important assistance in the literature review portion of the first phase effort and prepared an annotated bibliography regarding the potential effects of industrial noise on bowhead whales in the Beaufort Sea. That bibliography is contained in the interim report of this project (Miles et al. 1986).

PROJECT ORGANIZATION

Although the authors of this report have been responsible for specific sections, they have worked closely together in the review of the full document to ensure continuity of technical content. The scientists and their individual report and project responsibilities are:

Mr. Paul R. Miles: Program Manager and Project Scientist. Prepared the Executive Summary, Introduction and Objectives, and Study Area and Methods sections; and worked jointly with the other authors on the Conclusions and Recommendations sections. He was responsible for the overall management and coordination of the project and this report, and participated in the field measurement program.

Mr. Charles I. Malme: Field Measurement Manager and Assistant Project Scientist. Coauthored the sections regarding industrial and ambient noise measurements. He prepared the sections on acoustic propagation models, the responses of gray whales to acoustic stimuli, and possible responses of whales to variable sounds. He organized and directed the field measurement effort and directed and performed analysis of the 1986 field data.

Dr. W. John Richardson: LGL Ltd., environmental research associates, was contracted by BBN to use existing data on disturbance responses of bowhead whales, along with the acoustic environmental data obtained by BBN, to develop "zone of influence" projections. Dr. Richardson authored the sections on whale behavioral response analysis methods (Section 2.3), zones of influence for bowhead whales (most of Sections 3.4-3.6), and Appendices D and E.

In the preparation of the interim report under this project (BBN Report No. 6185, Miles et al. 1986), Mr. George Shepard, as data analysis manager, coordinated and performed analysis of the 1985 field data, the results of which are included here. He was also a key member of both the 1985 and 1986 field measurement endeavors.

EXECUTIVE SUMMARY

This report presents the results of a two year research effort concerning industrial noise sources associated with offshore oil exploration in the Alaskan Beaufort Sea and the anticipated behavioral responses of endangered whales to those sources. The basic purpose of the research was to estimate the distances between a sound source and whale where one may expect industrial noise (1) to be detected by whales, and (2) to elicit some behavioral response. The endangered whales of concern to this project are the bowhead whale (Balaena mysticetus) and gray whale (Eschrichtius robustus). Field work was required to develop a quantitative description of the acoustic environment, including definition of the sound propagation characteristics at planned and active offshore oil drilling sites. The first increment of that work was performed from 16 August to 19 September 1985 and the second field period ran from 15 August to 13 September 1986. An essential ingredient in this research was the use of historical data on responses of bowhead whales and gray whales to underwater noise from industrial sources. These data were derived in recent years by LGL Ltd. and BBN Laboratories, respectively.

Six offshore drilling sites in the Alaskan Beaufort Sea were selected by Minerals Management Service to be studied:

- Orion, a site in Harrison Bay, where the Concrete Island Drilling System (CIDS) was operated by Exxon; the CIDS was at the Orion site during 1985 but not in full operation, and was absent from the site in 1986; water depth, 14 m.

- Sandpiper Island, a man-made gravel island located northwest of Prudhoe Bay and used as a base for standard drilling equipment; operated by Shell in 1985 and by Amoco early in 1986; water depth, 15 m.

- Hammerhead Prospect, located north of Flaxman Island, was occupied by the drillship CANMAR EXPLORER II in 1985, on behalf of Union Oil of California (Unocal); water depth, 28 m.

- Corona, located off Camden Bay, was occupied by the drillship CANMAR EXPLORER II and its support vessels in 1986, on behalf of Shell Western; water depth 35 m.

- Erik and Belcher Prospects, located north and east of Barter Island, respectively; there was dredging at Erik in 1985 and no industrial activity at Belcher in 1985-86; operated by Amoco; water depths 40 m (Erik) and 55 m (Belcher).

Similarly, some acoustic data were acquired at Northstar and Seal Islands, two man-made gravel islands near Sandpiper, to supplement the description of the acoustic environment of the region.

The environmental conditions existing during the field measurement work were dominated by drifting sea ice and, at times, heavy winds. These conditions combined to permit acoustic measurements during only 15 days in 1985 and 15 days in 1986. The unusually heavy ice conditions in 1985 prevented the acquisition of any data at Hammerhead and hampered data acquisition at other sites. The acoustic data acquired by BBN have been supplemented with copies of 1985 data tapes obtained by Greeneridge Sciences, Inc., providing acoustic signatures from drilling on Sandpiper Island and by drillship CANMAR EXPLORER II at Hammerhead.

Measurements of ambient or natural background underwater noise were acquired at the above sites during 5-15 minute periods at random intervals during various days. The resulting recordings were analyzed to provide both narrowband and one-third octave band spectra. These data, along with historical data on wind and ice conditions, were used to derive cumulative distribution functions estimating the 5th, 50th and 95th percentile statistical levels of ambient noise experienced at each site. The resulting ambient noise data presented in this report are critical in calculating signal-to-ambient noise ratios, which are used in predicting the behavioral responses of whales.

The radiated noise or underwater sound signatures of two tugs working together at Sandpiper Island, one tug working with a dredge barge at Erik, a clam-shell dredge at Erik, EXPLORER II drillship operations at Hammerhead and Corona, icebreaker noise (open water and pushing on ice) and drilling on a gravel island at Sandpiper, were all acquired and analyzed. Both narrowband and one-third octave band analyses were performed. These sources of drillsite-related noise have been rank-ordered according to sound pressure level in dominant bands from the most to the least intense. They are (1) icebreaker pushing ice (heavy propeller cavitation), (2) tugs working (propeller cavitation), (3) icebreaker underway in open water, (4) dredge operating, (5) drillship drilling and (6) drilling from an artificial gravel island. This does not represent the entire variety of noise sources associated with offshore drilling, but the list is representative of the variety of sources of continuous and intermittent sounds. In contrast, regularly-repeating impulsive noises from air gun arrays used for seismic surveys are considerably stronger; seismic pulses are the most intense of all industrial noises routinely introduced into the sea in the Alaska OCS region.

Measurements of the sound propagation or transmission loss (TL) characteristics from each site toward the expected locations of whales were obtained, usually using a controlled sound source and measuring received sound level as a function of distance from that source. A second method used was to measure noise levels versus distance from some continuous industrial noise source associated with a particular site. Data were acquired in this manner to distances of 25 km. By recording and analyzing seismic survey impulses to distances of 40 km and greater from the seismic vessel, it was possible to estimate propagation loss characteristics to distances as great as 50 km. Acoustic transmission loss in shallow continental shelf waters where oil industry activities occur is very site-specific. Hence, there is a need to measure the TL characteristics of each site. These TL data are the most critical element in the description of the acoustic environment of migrating or feeding whales since only a quantitative description of the site-specific TL will permit valid predictions of industrial noise levels at expected whale locations. The measurements have demonstrated that, to a first approximation, a cylindrical spreading law applies at each of the sites visited. This law describes a loss of acoustic energy according to 10 log R (R = range from the source). Variations in ocean bottom and surface conditions at each site, e.g. bottom composition ice cover, and wave conditions, cause site-specific differences in the TL algorithms. At least in 1986, temporal changes in water-mass characteristics also affected TL. A strong sub-surface incursion of warm Bering Sea water near the shelf-break in September-October 1986, along with cooling of the surface water as freeze-up approached, enhanced propagation considerably at moderate frequencies.

Sub-bottom conditions also influence sound propagation. There is strong evidence that the presence of sub-sea permafrost and overconsolidated clay sediments contribute in an important way to unusually efficient sound transmission over the continental shelf of the Beaufort Sea. In fact, comparison of the TL characteristics in the Beaufort with those measured in similar water depths in more temperate ocean areas demonstrates that the Beaufort TL characteristics are unusually efficient; TL in other areas of similar water depth frequently is found to vary as 15 log R and sometimes as high as 25 log R in contrast to 10 log R in the Alaskan and Canadian Beaufort continental shelf regions.

The ambient noise statistics, industrial noise data and acoustic transmission loss data were combined in analyses performed by LGL Ltd. to estimate those distances from the sound sources where bowhead whales could be expected to detect and/or respond to the presence of industrial sounds. Zone of influence tables and figures are presented which relate predicted industrial sound levels at particular sites to historical data regarding whale response to acoustic stimuli. BBN has summarized similar research conducted in California and the Bering Sea on the behavioral responses of migrating and feeding gray whales to industrial underwater acoustic stimuli, and has discussed those data as they may apply to gray whale response in the Beaufort Sea.

Two acoustic criteria have been used in relating industrial noise levels to whale behavioral response: (1) predicted signal-to-noise ratio (S:N) in the l/3-octave band of highest S:N, and (2) absolute received sound pressure level in either that same l/3-octave band or in the effective bandwidth of the signal. Since it is not known at the present time which criterion is more important in eliciting response in bowhead and gray whales, both have been considered in developing behavioral response predictions. The analyses assume that either one or both of these two criteria represent the basic causal acoustic measure(s) affecting behavioral response.

Zones of responsiveness to industrial noise have been predicted for bowhead whales, which commonly inhabit the coastal regions of the Beaufort Sea in the summer and, to a limited extent, for gray whales (which are rarely seen in that region). Major offshore industrial noise sources generally fall into two categories: (1) those which radiate continuous or near-continuous sound, and (2) those which radiate intermittent sound that fluctuates in level, often in a significant way. The major emphasis of this report has been placed on predictions of zones of influence for continuous noise sources since it is that category for which there exists important prior research results concerning bowhead and gray whale behavioral response. Intermittent sources are an important element in the industrial acoustic environment of the Alaskan Beaufort, however, and hence the possible zones of responsiveness around intermittent sources are also discussed briefly. A third category, directly approaching vessels, has received limited attention here. Clear-cut responses of bowheads to directly approaching vessels have been observed.

Whales are assumed to be able to hear an industrial noise if its level equals or exceeds the background ambient level in the corresponding frequency band. Zones of audibility have been estimated for all industrial noise sources and industrial sites studied. These zones of audibility are larger than the zones of responsiveness, since whales are not expected to react overtly to most weak sounds even though those sounds may be audible.

The zones of responsiveness of bowhead whales to continuous noise sources typically, depending on site, have a radius of:

Two tugs in bollard condition (forcing barge against island)	1.6-12 km
Icebreaker underway in open water	2-12 km
Tug underway in open water	1-8 km
Drillship drilling on site	1-4 km
Drilling on artificial island	0.02-0.2 km.

Estimates of zones of responsiveness to continuous noise from industrial sources are considered to be reliable for the environmentally related sound propagation and signal-to-noise conditions assumed in these calculations. These radii are based on the observation that roughly half of the bowhead whales show avoidance responses (probability of avoidance of about 0.5) to industrial sounds which have a 30 dB S:N. A smaller proportion of the bowheads react when the S:N is about 20 dB, which would occur at greater ranges than those summarized above and a few bowheads may react with even lower S:N (i.e., at even longer ranges) . On the other hand, some bowheads apparently tolerate S:N ratios as high as 40 dB without exhibiting an avoidance reaction; for those individuals the zone of responsiveness is smaller. Thresholds of responsiveness are likely to be lower than average (i.e., larger zone of responsiveness) in the cases of rapidly increasing sounds. Thresholds may be higher than average (i.e., small zone) in the cases of continuous "non-threatening" sounds.

Zones of responsiveness around intermittent sources of sound are discussed using two alternative assumptions, since whale responsiveness to this type of source has not been studied: (1) that they respond as man does, to the average acoustic energy being received over a specific period of time and as bowheads and gray whales react to seismic sounds and (2) assuming that the whales respond as they would to continuous noise with level equal to the highest level of noise radiated during a time series of fluctuating signals. Analysis using these assumptions and a 30 dB S:N criterion yields the following radii:

Icebreaker pushing ice	4.6-20 km
Tug towing loaded barge	0.3-9.3 km
Clamshell dredge working	0.1-3.1

The lower values relate to the second assumption and are based on the duty cycle of observed fluctuations in sound levels radiated by these sources over a finite period of time. Duty cycle is the ratio of the operating time of an intermittent sound source to a total period of exposure potential. Presently available data are insufficient to show which assumption is more appropriate. Values for the icebreaker pushing ice are higher than for any continuous source because this was the strongest noise source studied.

The following estimates of the zones of responsiveness of gray whales in the Beaufort Sea to drillship noise are based on the absolute level criterion. The estimates have been calculated for 0.1 and 0.5 probability of avoidance corresponding to received levels of 110 dB and 120 dB re 1 μPa, respectively, in the dominant frequency band, which generally included several l/3-octaves. The radius of the zone of responsiveness is again site-specific.

Drillship Noise:	110 dB re 1 μPa	120 dB re 1 μPa
Probability of Avoidance:	0.l	0.5
	Est. Range (Zone of Responsiveness)	
Belcher	9.6 km	0.9
Erik	5.9	2.0
Corona	4.8	1.4
Hammerhead	9.1	2.1
Sandpiper	8.1	3.3
Orion	8.6	3.3

Based on the signal-to-noise ratio criterion, about half of the gray whales show avoidance responses when the signal-to-noise ratio is 20 dB rather than the 30 dB which characterizes bowhead response. The difference may reflect the different bandwidths considered for the two species. For gray whales, the zone of responsiveness to drillship noise, based on the 20 dB S:N criterion, varies from 5-9 km depending on drillsite.

It should be noted that the natural ambient level varies widely from day to day. Consequently, the radius where S:N is 20 or 30 dB also varies widely. The radii quoted above refer to median ambient conditions. Considerably larger or smaller radii of responsiveness can be expected on days when ambient noise levels are lower or higher, respectively. Natural variability in sound propagation conditions can also affect predicted radii of responsiveness based on any of the response criteria.

For the details of this two year research effort, please refer to the body of this report and the supporting appendices.

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1. INTRODUCTION AND OBJECTIVES

The continuing exploration for and development of oil and gas resources in the Alaskan Beaufort Sea Outer Continental Shelf (OCS) region, has created a need for investigations relating to potential environmental impact. One issue is the extent to which industrial acoustic stimuli may influence the behavior of' endangered whales. The bowhead whale (Balaena mysticetus), in particular, frequents the Beaufort Sea from April into October (e.g. Braham et al. 1980; Ljungblad et al. 1985a, 1986 a,b, 1987), including areas of oil and gas exploration and development. The gray whale (Eschrichtius robustus) also feeds in the Arctic during summer months, although this species is not sighted frequently in the Beaufort (Braham 1984; Marquette and Braham 1982). Concern regarding potential environmental impact has centered largely on these two endangered species. In the process of developing a quantitative understanding of whale behavioral response to acoustic stimuli, it is necessary to quantify the underwater ambient noise characteristics, the acoustic signatures of various industrial activities, and the site-specific underwater sound propagation characteristics of the region in order to predict sound levels at potential whale locations. The resulting data must be combined with the results of research into the behavioral response of whales to acoustic stimuli obtained through extensive observation of behavior under natural undisturbed conditions, during disturbed conditions from uncontrolled "intrusions" by industrial activity, and during controlled experiments. Statistical analysis of the resulting data provides the needed understanding of the behavioral response of whales to acoustic stimuli as a function of such variables as ambient background noise and the frequency content and level of the sounds (which vary with distance between the industrial sound source and whale).

Accordingly, the Minerals Management Service (MMS) contracted BBN Laboratories Incorporated and their subcontractor, LGL Ltd. environmental research associates, to perform a two-year research project to develop the needed quantitative understanding of whale behavioral response to acoustic stimuli at specific sites in the Alaskan Beaufort Sea. Required tasks under the project include measurement and modeling of the acoustic environment at selected sites in the Alaskan Beaufort Sea OCS during the 1985 and 1986 summer/fall seasons by BBN and the use of the resulting data by LGL and BBN to predict the distances from the sites at which whales might respond. Field measurements, behavioral observations, and analytical experience gained by BBN and LGL in previous research projects regarding environmental acoustics and the responses of bowhead, gray and humpback whales to controlled acoustic stimuli (Malme et al. 1983, 1984, 1985, 1986a; Richardson 1985; Richardson, et al. 1985a,b,c) are key elements in the design and performance of this project. The following purpose and objectives of this project are quoted from the contract.

Purpose

The purpose of this project is to provide information necessary to predict the range at which bowhead and gray whale behavior is likely to be influenced by sounds produced at specific offshore drilling sites.

Objectives

The objectives are to develop and implement a research plan in the Beaufort Sea lease sale area to:

A. Acquire measurements of the acoustic environment prior to the onset of industrial operation.

B. Measure transmission loss characteristics of sounds associated with activities of each offshore drilling site concurrent with the major period of exploration (in 1985 and 1986) resulting from Diapir Field Lease Sales (Beaufort Sea) 71 and 87.

C. Monitor the characteristics of sounds associated with offshore drilling sites throughout the study period. As appropriate for the specific site, marine geophysical sounds will also be monitored as a secondary focus.

D. Synthesize, through mathematical/statistical techniques, the results of objectives A–C with data and/or simple models of bowhead and gray whale response to sounds associated with offshore drilling activities in order to develop site-specific "zone of detection/potential influence" projections.

E. Coordinate with ongoing endangered species studies in the Beaufort Sea area and maintain appropriate liaison with local residents and government agencies.

F. Prepare appropriate tabular or graphic results, synthesize with other recent literature and report findings.

This final report summarizes the measurements made during the 1985 and 1986 field seasons (16 August-19 September and 15 August-13 September, respectively) and presents the results of the analyses performed on the field data, the synthesis of whale response in the context of the acoustic environment, and the derivation of zones of potential influence on whales. An interim report was prepared on the findings of this project for the 1985 field season (Miles et al. 1986). Most of the 1985 as well as the 1986 results are presented here.

Over the two years, data were acquired at six sites in the Alaskan Beaufort Sea:

- Orion (Exxon),
- Sandpiper (Shell and Amoco),
- Hammerhead (Unocal),
- Corona (Shell)
- Erik (Amoco),
- Belcher (Amoco).

Details on location and industrial activities at these sites are provided in Section 2. A good sampling of representative industrial noise associated with oil industry operations in the Alaskan Beaufort Sea was obtained during the 1985 and 1986 measurement seaons. Greeneridge Sciences, Inc. (Dr. Charles Greene) was also performing acoustic measurements under separate projects at three of these sites in 1985 and 1986. The industrial noise data matrix being compiled under this project was supplemented with some of the Greeneridge Sciences data (including some of their 1980-84 data from the Canadian Beaufort Sea), with approval from their clients, to provide a more complete summary. Detailed results from the Greeneridge studies in the Alaskan Beaufort are given in McLaren et al. 1986, Johnson et al. 1986, and Greene (in preparation).

Parts of both the 1985 and the 1986 field seasons were dominated by heavy drifting sea-ice conditions. After encountering the problem in 1985 using the fiberglass hull M.V. JUDY ANN, which was limited to operating in no more than 2/10 ice cover and in relatively light seas, it was decided to arrange for chartering a steel-hulled larger vessel for 1986. The M.V. ARCTIC ROSE was obtained, allowing work in heavier ice and sea conditions. Even with this improved capability, 10 field days were lost to the project because of ice and heavy wind in 1986. An additional reason for the larger vessel was the need for handling equipment capable of deploying and retrieving the heavier instrumentation required for acquisition of long-range acoustic sound propagation loss data. As a result, most of the acoustic environmental data needed in 1986 to supplement the 1985 data were acquired successfully. The eastern-most sites (Hammerhead, Corona, Erik, and Belcher) received first priority in 1986. Primary emphasis was on Corona, which was the only industrially active site in August and early September 1986. The drillship operating at Corona moved to Hammerhead late in September, following the BBN measurement period.

As noted in the stated purpose of this research project, the potential for behavioral response of both bowhead and gray whales to industrial acoustic stimuli in the Alaskan Beaufort Sea must be evaluated. While the dominant endangered whale species in that area is the bowhead, gray whales are observed occasionally in the western regions of the Beaufort Sea and in the eastern Chukchi Sea (Braham 1984, Ljungblad et al. 1985a, Marquette and Braham, 1982). Some have also been seen at times near Prudhoe Bay, and near Tuktoyaktuk in the Northwest Territories (Rugh and Fraker, 1981; Richardson, 1985). The primary summer feeding grounds of the gray whale are in the Northern Bering Sea and Southern Chukchi Sea regions (Braham 1984). All of these areas are candidates for oil exploration and development. While the major thrust of this report relates to the bowhead whale, some attention is given to predicting gray whale zones of influence. BBN has performed research studies (Malme et al. 1983, 1984, 1986) regarding behavioral responses of migrating and feeding gray whales to controlled acoustic stimuli (playback of underwater sounds associated with oil and gas exploration and development). This report discusses the anticipated responses of gray whales to acoustic stimuli in the Alaskan Beaufort Sea by applying the results of BBN studies of migrating gray whales in California and feeding gray whales in the Northern Bering Sea and using the acoustic environmental data in the Beaufort obtained under this research project.

Section 2 of this report provides details of the study area and methods used to acquire the acoustic data needed near the selected sites. Also described are the analytical methods used to estimate potential zones of influence based on the new acoustic data plus existing data on behavioral responses to noise. The results of the 1985 and 1986 portions of this project are presented in Sec. 3 including

- a statistical description of the short-term ambient noise environment,
- levels and frequency characteristics of the underwater industrial sounds measured at various sites,
- sound propagation characteristics of each site (acoustic models), and
- estimated zones of potential influence for each combination of industrial noise source and site.

Conclusions and recommendations developed during this research project, which encompassed two field measurement seasons in the Alaskan Beaufort Sea, are given in Section 4 followed by a listing of cited literature (Section 5). Appendix A outlines bowhead whale migration corridors in relation to selected drillsites in the Alaskan Beaufort Sea. Appendix B presents typical short-term ambient noise statistics for the Orion, Sandpiper, and Corona drillsites. Appendix C provides a listing of the shallow water acoustic transmission loss program used during this project as well as a tabulation of TL characteristics. Appendix D presents sound propagation estimates used in calculating zones of influence of various industrial sources at each site. Appendix E provides, for the various sites, detailed zone of influence lookup tables usable for any source of continuous industrial noise. Appendix F is a tabulation of one-third octave band frequency allocations by band number to assist the reader in interpretation of some of the drillsite noise spectra included in Section 3.2.

One Appendix contained in the previous report on this project (Miles et al. 1986) which may be of interest to the reader is the 88 page Appendix B "Previous Data on Responses of Bowhead and Gray Whales to Noise from Oil and Gas Industry Activities ." It will be referred to in this report, however, leaving it to the reader to investigate later if he desires a historical review. Also, Appendix C in that earlier report contains an annotated bibliography of selected literature regarding bowhead whale research in the Beaufort Sea. That Appendix has also been excluded from this Final Report of the project.

2. DESCRIPTION OF THE STUDY AREA AND METHODS

2.1 The Study Area and Selected Sites

The underwater acoustic environment of six actual or planned offshore drilling sites distributed along the Alaskan Beaufort Sea continental shelf was measured during the summers of 1985 and 1986 to serve as a basis for predicting industrially-related sound levels of noise as a function of distance from those sites. The purpose of that effort has been to provide the information needed to estimate zones of responsiveness of endangered whales to industrial noise associated with operations at typical sites. Figure 1 provides locations of the six sites which range from the most westerly site, Orion near Harrison Bay, to Belcher 408 km or 220 miles to the east, located north of Demarcation Bay. All sites except Hammerhead were visited for making acoustic measurements in 1985. Data were acquired at all sites except Orion in 1986, although only Corona provided industrial noise data. As shown in Figure 1, two sites are located in water shallower than 18 meters and the remaining four are in deeper water, ranging from 28 meters at Hammerhead to 55 meters at Belcher. Table 1 provides general information about the six drillsites and industrial activity during the acoustic measurement periods (16 August-19 September 1985 and 15 August-13 September 1986).

On the following pages we describe briefly a few environmental factors and bowhead whale migration and feeding habits which are relevant to the objectives of this study. Details of acoustic measurement and analysis methods and whale behavioral response analysis methods are also provided. Additional details on these subjects were contained in the 1985 field season report (BBN No. 6185, Miles et al. 1986) prepared under this contract. Excerpts from Section 2 of that report are included as Appendices A and B of this report for quick reference purposes.

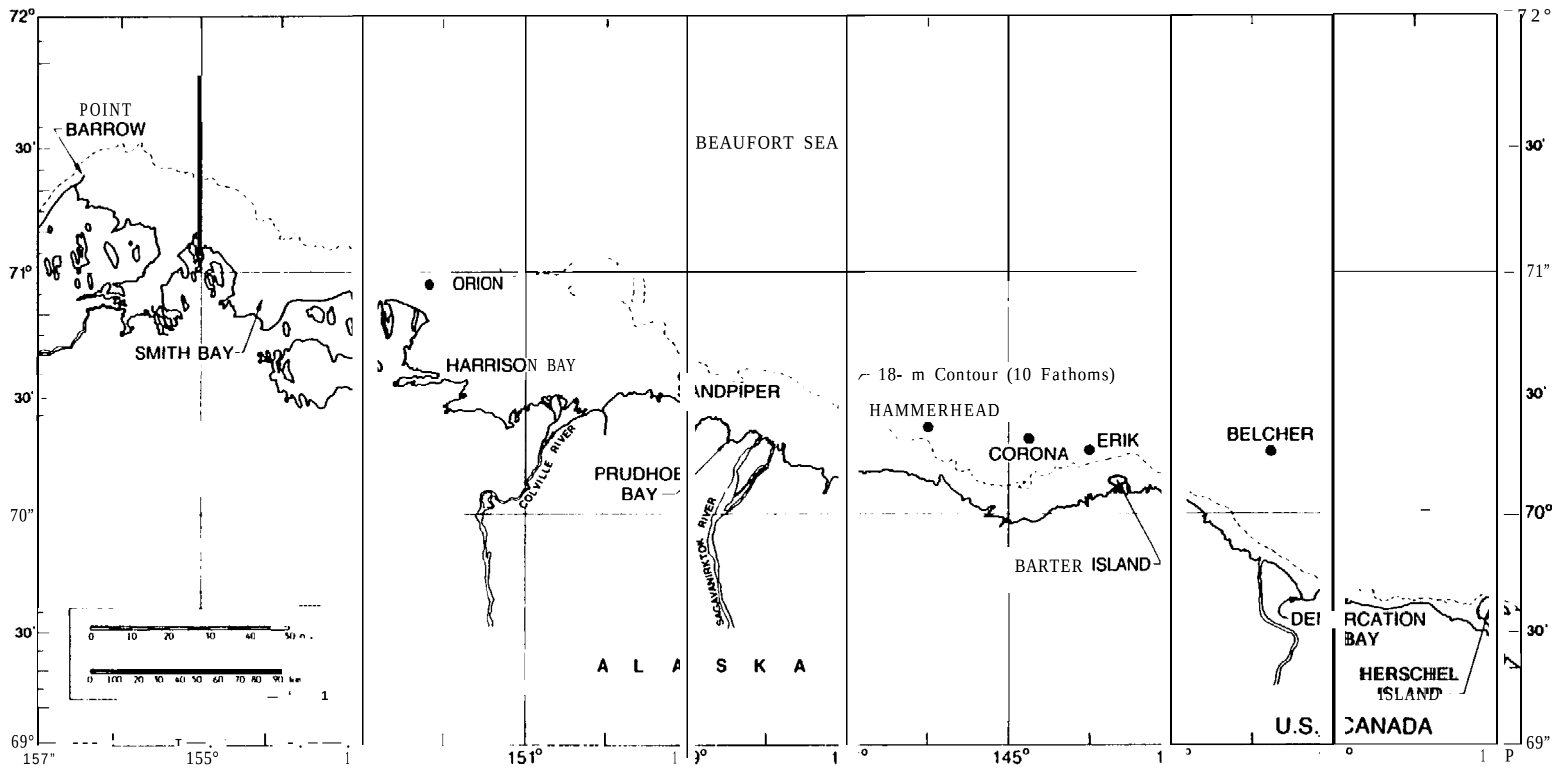


FIG. 1. SELECTED MEASUREMENT SITES IN THE ALASKAN BEAUFORT SEA.

TABLE 1. **GENERAL DETAILS OF SELECTED MEASUREMENT SITES** IN THE ALASKAN BEAUFORT SEA.

Site	Area	Approx. Coordinates	Approx. Water Depth meters	Operator	Comments
Orion	Harrison Bay	70°57.41'N 152°03.78'W	14	Exxon	Glomar Beaufort Sea I Concrete Island Drilling System (CIDS) -- 1985
Sandpiper	Northwest of Prudhoe Bay	70°35.08'N 149°05.81'W	15	Shell 1985 Amoco 1986	Artificial gravel island, drilling preparations, and support vessels 1985,* no activity late summer 1986
Hammerhead	North of Flaxman Is.	70°21.88'N 146°01.47'W	28	Unocal	CANMAR EXPLORER II -- 1985* (drillship not on site during BBN measurements)
Corona	N. of Camden Bay	70°18.88'N 144°45.53'W	35	Shell	CANMAR EXPLORER II -- 1986 with drillship support vessels ROBERT LEMEUR, KIGORIAK (ice breakers), and three supply vessels.
Erik	N. of Barter Is.	70°16.6'N 143°58.67'W	40	Amoco	Dredge and Tug -- 1985 No activity -- 1986
Belcher	N. of Demarcation Bay	70°16.4'N 141047.0'W	55	Amoco	No operations on site either 1985 or 1986

*In 1985, Greeneridge Sciences Inc. provided underwater noise data from Sandpiper Island drilling operations and EXPLORER 11 drilling at Hammerhead (cf. McLaren et al. 1986).

2.1.1 Ocean bottom conditions

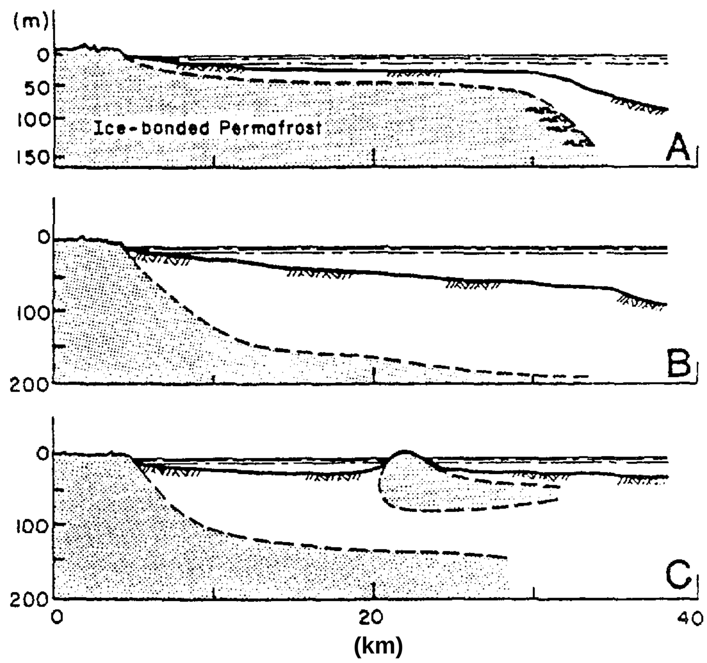
There are several important variables which influence the propagation characteristics of underwater sound, including water depth, the speed of sound (which in turn varies primarily with water temperature and salinity) and the physical characteristics of the ocean surface (roughness and ice cover) and ocean bottom. There is ample evidence (for instance, see Urick 1983) that the types and thicknesses of materials in the ocean bottom can cause significant differences in propagation characteristics as the acoustic energy interacts with the sand, silt or clay sediments. Exposed or sub-bottom regions of hard layers of bedrock, semi-consolidated and consolidated sediments often result in more efficient sound transmission than would occur with thick absorptive soft materials such as silt and clay. More will be said about site-specific sound propagation loss and the influence of the ocean bottom in Sec. 3. It is useful here, however, to discuss briefly the ocean bottom characteristics in the Beaufort Sea study area. The major region of interest lies on the continental shelf and south of the shelf edge or shelf break which, in the Alaskan Beaufort, occurs at a depth of 50-70 meters (27-38 fm) and about 65 km from shore. The average slope of the ocean bottom on the continental shelf and north to at least 20 km seaward from the selected sites is 0.02 degrees at Sandpiper, 0.04 degrees at Hammerhead, 0.06 degrees at Orion and Corona, 0.06 to 0.16 degrees at Erik and about 0.04 to 0.6 degrees at Belcher. While these slopes are small, they do have an important influence on long range sound propagation. The increasing steepness of the bottom slope north of the shelf break averages about 0.85° in the first 18 km (10 n.m.) and 2.0° in the second 18 km.

Bottom materials at the water/bottom interface on the shelf are quite site-specific and poorly sorted but generally grade from sand and gravel near shore (except inside the barrier islands where silt and clay (or "mud") is common) to medium and fine sand, silt, and clay offshore, near the 200 meter contour (Barnes and Reimnitz 1974; Morack and Rogers 1984; Naidu et al. 1984). Sediment thicknesses below the water/bottom interface and above the bedrock interface in the vicinity of the sites apparently can be 750 meters or greater (Neave and Sellman 1984).

Two forms of acoustically reflective intermediate layers occur within the oceanic sedimentary column of the Beaufort Sea continental shelf: (1) subsea permafrost or ice-bonded sediments and (2) overconsolidated clay. These layers are important to discuss since they almost certainly influence underwater sound propagation. In fact, as will be discussed in Section 3, some low frequency sound propagation measurement results can be explained only by assuming a reflective surface occurring at a depth below the water/bottom interface which corresponds to suspected depths of subsea permafrost zones.

Ice-bonded subsea permafrost zones are commonly encountered in drilling operations offshore and have been attributed to relict permafrost which formed offshore approximately 18,000 years ago when sea level fell to a minimum (Morack and Rogers 1984). These zones appear to be quite variable in thickness and horizontal extent. Seismic refraction and reflection survey data and physical sampling have located subsea permafrost at less than 10 meters below the near shore water/bottom interface to 20-40 meters as far as 20-60 km (11-32 n.m.) offshore from Prudhoe Bay and Harrison Bay (Morack and Rogers 1984; Neave and Sellman 1984). The depths to this ice-bonded sediment zone are quite variable both locally and from area to area. Based on careful analysis of seismic reflection data and substantiation of suspected subsea permafrost layers with borehole sampling, Neave and Sellmann (1984) have found that three general patterns frequently describe subsea permafrost distribution. Figure 2 (their Figure 12) demonstrates that subsea permafrost is often encountered 10 to 20 meters below the water/bottom interface as well as at a depth of 100-150 m below that interface. In the vicinity and offshore of barrier islands (where permafrost is at the surface) the relict sub-sea permafrost often occurs as a 20-40 meter layer within the bottom starting at a depth of 10-20 meters and above unfrozen sediments which, in turn, overlay a deep permafrost zone (Fig. 2c). Thicknesses in some areas may be several hundred meters and seismic refraction data indicate a probable permafrost zone as deep as 200 to 450 meters. Neave and Sellmann (1984) also present data which strongly indicate that both Orion in Harrison Bay and Sandpiper near Prudhoe will in all likelihood have subsea permafrost zones extending seaward from those sites. It is probable that ice-bonded sediments also exist at Hammerhead, Corona, Erik, and Belcher and extending offshore. These layers exhibit high seismic compressional wave speeds providing a strong acoustically reflective zone. Figure 3 in the interim report on this project (Miles et al. 1986) was adapted from Morack and Rogers (1984) and expanded to include typical "hard-rock" sound speed data. That figure demonstrated the compressional wave speed contrasts between unbended and ice-bonded sediments (which in turn are similar to wave speeds in some types of rock). In ice-bonded sediments, it is common to measure wave speeds of 2500 m/see to over 4000 m/see compared to 1400 to 2000 m/see for water-saturated sediments providing the needed compressional wave speed contrast for an acoustically reflective interface.

While the major objective of this research is to consider the acoustic environment, including sound propagation characteristics in the Alaskan Beaufort Sea, it is useful to establish that subsea permafrost zones have been found and reported at similar depths below the water/bottom interface in the Canadian Beaufort Sea. Blasco (1984), Hunter (1984), Hunter



From Neave and Sellman (1984)

FIGURE 2. THREE SUBSEA PERMAFROST DISTRIBUTION PATTERNS INTERPRETED FOR THE REGION STUDIED IN THE BEAUFORT SEA: A, SHALLOW RELICT PERMAFROST, B, DEEP RELICT PERMAFROST, AND C, LAYERED ICE-BONDED PERMAFROST.

and Hobson (1975), and Morack et al. (1983) have reported subsea permafrost zones which are very similar to the three distribution patterns reported by Neave and Sellman (1984) for the Alaskan Beaufort, and extending as far as 130 km from shore. As noted previously, these permafrost zones are quite variable in thickness and surface topography but they are frequently encountered and probably do influence underwater sound propagation characteristics in the continental shelf regions of the Beaufort Sea.

It has also been suggested* that overconsolidated bottom and sub-bottom sedimentary layers, primarily in the form of dense clay, could also contribute to acoustic reflectivity. Laboratory tests and field observation of environmental parameters such as water and sediment temperatures and pressures indicate that exposure to many freeze-thaw cycles is a probable major contributor to the overconsolidation of the clay and silty-clay sediments. The result is a material which is nearly impervious to diver-operated sampling devices and is widespread and geometrically homogeneous to depths of 20-m or more off the North Slope.* It is entirely possible that this dense clay zone works in concert with subsea permafrost regions to provide efficient acoustically reflective regions which strongly influence acoustic propagation. More will be said on this subject in Section 3 regarding the site-specific acoustic propagation measurements and models.

2.1.2 Whale migration

Appendix A contains a brief summary of usual bowhead whale migration characteristics including an approximate layout of

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*personal communication: Paul V. Sellmann, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH, 3/12/86.

spring and fall migration corridors with respect to the six industrial sites considered in this study. Gray whales are rarely seen east of Point Barrow and hence no migration corridor can be assumed. Ljungblad et al. (1985a, 1985c, 1986a,b), Hickie and Davis (1983), Davis et al. (1985), Carroll and Smithhisler (1980) and numerous others all discuss migration and feeding characteristics of the bowhead. Generally, the spring migration of bowheads eastward occurs in the April-early June time period following leads in pack ice of 8/10 to 10/10 cover from near Point Barrow to as far as 90 to 170 km from shore to their main feeding grounds in the Canadian Beaufort. They are well beyond expected influence from whatever continental shelf industrial noise may exist in that time period. However, the westward fall migration of the bowhead in late August to mid-October is closer to shore. The southern boundary of the corridor corresponds approximately to the 18-m depth contour shown in Fig. 1, although some bowheads occur even closer to shore (Johnson 1984; Richardson et al. 1987). There is evidence that the bowheads feed at least during the early phases of the westward migration before heavy ice starts to form near shore (Ljungblad et al. 1986a; Richardson et al. 1987). The corridor appears to be 50 to 80 km wide in the regions of the six industrial sites but whale counts appear to be heavily skewed to peak between the 18-m contour and the shelf break approximately 65 km from shore. The Orion and Sandpiper drill sites are located south of the southern boundary of the migration corridor while the remaining four industrial sites are in water >18 m deep and are within the general fall migration corridor.

2.2 Acoustic Environment Measurement and Analysis Methods

In achieving the objective of this project, the acoustic environment of the Alaskan Beaufort was defined before any site-specific analysis of potential whale behavioral response could be accomplished. The acoustic environmental measurements were scheduled to span two summer periods in 1985 and 1986 because of the seasonal variability of industrial activity at the sites of interest to this project, fluctuating weather and sea-ice conditions, and limited duration of the measurement season. The underwater acoustic environment during those periods was investigated by obtaining measurements of the ambient or natural background noise and its variability (with minimal contributions from industrial activity), the underwater radiated noise signatures of the various industrial operations at selected sites, and the underwater sound propagation characteristics (transmission loss or TL) as a function of distance from each site. Analysis of the resulting data provided the means for predicting industrial noise level as a function of distance or range from each site and for evaluating the detection of those sounds by whales in the presence of typical sound level variations of ambient noise.

The interim report of this project (Miles et al. 1986) summarized the results of the 1985 field measurement work, providing estimates of potential zones of responsiveness of whales to typical offshore oil industry sounds. Detailed discussions of acoustic measurement and analysis methods were included in that report. The second season measurement work in the Beaufort in 1986 provided additional oil industry noise data, but more important, it provided long range sound propagation data, reducing the need for extrapolation of short range TL data to long distances as had to be done in the 1985 field-season report. The following discussion of acoustic measurement procedures and analysis methods for the two season project contains much of the material presented in the interim report to avoid the need for frequent references to that report. The major differences in the measurement systems used in 1985 and 1986 relate to the need to obtain long range TL data in the second season.

Acoustic measurements in 1985 were made from M.V. JUDY ANN, a 13-m fiberglass vessel which was a good platform for the project but was limited to working in light sea ice conditions (2/10 cover) and moderate seas (state 3 or less). However, a larger, steel-hulled vessel was sought when it was determined that operations in 1986 during more severe environmental conditions would be required for the acquisition of long range acoustic TL data with larger and heavier measurement equipment than that used in 1985. M.V. ARCTIC ROSE (35m overall length) became available to the project in 1986. That vessel had a hydraulic winch capable of overside deployment and retrieval of the sound source system and a large 5-m remote recording sonobuoy, each weighing about 114 kg (250 lb).

Tables 2 and 3 provide a summary of the acoustic measurements performed in 1985 and 1986. During the two years, sufficient data were acquired at all six selected sites which are, listed in order from west to east, Orion, Sandpiper, Hammerhead, Corona, Erik, and Belcher. Some data were also obtained at three other sites (Northstar Island, Seal Island, and Tenneco SSDC). The parenthetical numbers in the table indicate the number of measurements or tests of each parameter at each site. The resulting data provide a description of the acoustic environment and site-specific characteristics of the Alaskan Beaufort Sea continental shelf area.

The sound transmission loss data resulting from measurements at each of the sites demonstrate the variability of TL throughout the region, emphasizing the importance of establishing site-specific acoustic characteristics for the purposes of this project. TL data obtained in 1985 were limited to maximum distances of 4 to 5 km due primarily to vessel and ice limitations. TL curves were extrapolated beyond that range in the interim report of the project through use of previously reported

TABLE 2. BEAUFORT SEA MEASUREMENTS (Test Period: 16 AUGUST - 19 SEPTEMBER 1985).

Site	Ambient Noise	Sound Transmission Loss (TL)	Sound Speed Profile	Signatures and Comments
Orion, Harrison Bay	8/28 (2) 8/29 (2)	8/28 8/29	8/28 (2) 8/29 (1)	8/28 Downhole pulsing GLOMAR BEAUFORT SEA I
Sandpiper Island	8/25 (3) 8/27 (1) 9/01 (1) 9/05 (4)	8/27 8/30	8/25 (2) 8/27 (1) 9/01 (1) 9/05 (1)	8/25 Two workboats (distant) 8/30 Two tugs opposite side of island Whale calls during TL 9/05 Drilling scheduled but not detected
Hammerhead	None			Ice conditions prevented access
Corona Prospect	9/08 (2)		9/08 (1)	No activities on site
Erik Prospect	9/09 (9) 9/13 (6)	9/13	9/09 (1) 9/13 (1)	9/09 Clam-shell dredge and tug 9/13 Clam-shell dredge and tug; air gun in background
Belcher Prospect	9/10 (3) 9/11 (1)	9/10 9/11	9/10 (1) 9/11 (1)	No activities on site
Northstar Island	9/01 (1) 9/03 (1) 9/04 (1)	9/01	9/01 (1) 9/03 (1) 9/04 (1)	9/01 Island construction activity
Seal Island			8/18 (1)	No activities on site

Notes: 1) Parenthetical numbers denote number of measurements or tests.

2) Ambient noise segments are 5 to 15 minutes long.

3) Sound source **for TL** experiments: single J-13 transducer

4) Acoustic signature tape data from Greeneridge Sciences (notin table)

5) Days: Acoustic measurements (15); weather/ice/vessel maintenance (13); transit time (4); preparation (3); 35 day charter period (M.V. JUDY ANN)

(1) Hammerhead; CANMAR EXPLORER II Drillship 8/27-28/85
(2) Sandpiper Island; drill rig 10/17/85
(3) Corona Site; Icebreaker 10/21/85

TABLE 3. BEAUFORT SEA MEASUREMENTS (TEST PERIOD: 15 AUGUST - 13 SEPTEMBER 1986).

Site	Ambient Noise	Sound Speed Profile	Sound Transmission Loss (TL)	Comment: Signatures	Comment: Industrial Activities
Orion					No data
Sandpiper	9/11 (1) 9/12 (1)	9/11 (2)	9/11, J-13 Short range 9/11, J-13 East		None
Hammerhead	9/09 (1)	9/09 (2)	9/09, J-13 Short range 9/09, J-13 NW		None
Corona	9/03 (4) 9/04 (4) 9/10 (1)	9/02 (2) 9/03 (2) 9/04 (2) 9/10 (21)	9/02, J-13 North 9/02, Seismic array 9/03, J-13 East 9/03, Seismic array 9/04, Seismic array 9/10, J-13 North	EXPLORER II Icebreaker (KIGORIAK) Icebreaker (LEMEUR) (various operational conditions)	Drillship: EXPLORER II Icebreakers: ROBERT LEMEUR CANMAR KIGORIAK Supply Vessels: SUPPLIER 2,4,7
Erik	8/18 (1) 8/28 (1) 8/30 (1) 8/31 (1)	8/18 (2) 8/28 (1) 8/30 (2) 8/31 (1)	8/18 Seismic array 8/30, J-13 North	Icebreaker (ROBERT LEMEUR) -- Transiting	None
Belcher	8/19 (1) 8/20 (1) 9/06 (2)	8/20 (2) 9/06 (1) 9/07 (2)	8/20, J-13 East 9/06, J-13 East 9/07, J-13 North		None
Tenneco (SSDC)					No data (weather) (Eastern Harrison Bay)
Other	8/26 (1)				0.8 ice cover near Pokok Bay"

NOTES: 1. Parenthetical numbers denote number of measurements

2. Ambient noise segments are 5 to 15 minutes long

3. Sound sources for TL experiments: J-13 transducer pair or WESTERN POLARIS seismic survey air gun' array

4. Days: Acoustic Measurements = 15
Weather/ice = 10
Transit time between sites = 3
Mobilization/Demobilization = 2

30 day charter period (M.V. ARCTIC ROSE)

seismic survey data (Ljungblad et al. 1985b) coupled with analytical sound propagation modeling. In 1986 with the larger research vessel and a remote recording sonobuoy, TL data were acquired for distances of 20 to 50 km from the selected sites using the J-13 sound transducer pair and air gun array impulses from WESTERN POLARIS, a seismic survey vessel of opportunity. WESTERN POLARIS, operated by Western Geophysical, Inc., in the eastern Alaskan Beaufort in 1986, cooperated with this research project by providing information permitting estimation of long distance waterborne sound propagation loss.

Underwater radiated noise signatures were obtained for offshore oil industry sources operating at or near the sites. These were tugs, a clamshell dredge, a drillrig operating on Sandpiper Island (Greeneridge Sciences data), the CIDS structure GLOMAR BEAUFORT SEA I, drillship CANMAR EXPLORER II, and icebreakers ROBERT LEMEUR and CANMAR KIGORIAK. Supply vessel noise was also obtained during measurements in 1986 at Corona. However, more than one supply vessel often worked with the drillship at a given time, invalidating the possibility of deriving an acoustic description of a single supply vessel. Additional data were acquired from Greeneridge Sciences from acoustic measurements performed at Hammerhead and Sandpiper Island in 1985 at a time when industrial activities were proceeding (Johnson et al. 1986; McLaren et al. 1986). It was arranged through MMS, LGL, Unocal, and Shell to obtain copies of the Greeneridge taped signatures noted in Table 1.

Sound speed profile data were derived by BBN from measurements of water temperature and salinity at each site as a function of depth as described in detail later in this section. Also, it was learned through LGL that NOAA-Anchorage (under MMS sponsorship) was making detailed measurements of salinity and temperature vs depth from icebreaker POLAR STAR in early October over long transects running northerly from nearshore in the Alaskan Beaufort in the areas of interest to this project. Those transects ran from near the 18-m contour to beyond the shelf break. Important data were acquired during the latter phase of the bowhead migration in October, after the BBN field project was completed. NOAA provided typical profile data to this project through LGL. These data proved to be very important from the standpoint of estimating underwater sound propagation characteristics during the fall (late in the whale migration period), just before intrusion of heavy pack ice and freeze-up. The implications of the POLAR STAR data are discussed in detail in Section 3 of this report.

As noted in Tables 2 and 3, weather, pack ice and vessel maintenance (in 1985) limited acoustic measurements to 15 days out of a 35 day charter in 1985 and to 15 days out of a 30 day charter in 1986.

Results of the analysis of the data cataloged in Tables 2 and 3 are provided in Section 3. Presented below are brief discussions of the measurement and analysis"methods applied under this project.

2.2.1 Measurement systems

Ambient noise data should be acquired at the selected sites either prior to the onset of industrial activity or, at least, during periods when such activities are intermittent or at a minimum. Such data on natural background noise are needed to compare with industrial noise data measured at each site, and to determine the potential zone of influence on whales. Ideally, an ambient noise model should be developed which could predict noise spectrum levels at each site as a function of easily measurable environmental parameters (e.g., sea state and percent ice cover).

Unfortunately, past experience in the Arctic and in more temperate regions has shown that the relationship between noise level and the environment is a complex function and is dependent on a large number of environmental parameters. Accurate models require extensive amounts of data recorded over long periods of time. Clearly, this is beyond the scope of this project; but the work discussed in this report is presented as a step toward that goal. Our approach is to develop a simple empirical model which provides a statistical characterization of the ambient noise field. Five- to 15-minute recordings of ambient noise are recorded at various intervals during the more lengthy period of site occupation. Analysis of the resulting data provides a statistical sample of the ambient noise conditions at that site under the conditions prevailing at the times of recording. In addition to recording ambient noise at each site, it is necessary to document physical factors which influence background noise, such as sound speed profile, water depth, ice cover, sea state, wind speed, wind and wave directions and measurement hydrophore depth.

In addition to logging the above noted physical variables, which influence received levels of industrial noise as well as ambient noise characteristics, it is necessary to measure and log the distance between the measurement system and the industrial noise source. Similarly, the measurement of industrial noise data requires close coordination or communication with the industrial operator to relate any changes in received sound to specific industrial functions.

Measurements of the sound propagation or transmission loss (TL) characteristics associated with each site are a critical element in developing the ability to predict potential industrial noise levels at expected positions of whales. These site-specific measurements were accomplished through controlled projection of bands of noise from an underwater sound projector at the research vessel and measurement of sound received from that projector as a function of distance using either a second vessel (an inflatable AVON) in 1985, or a remotely-moored recording buoy in 1986. Measurements were made out to distances of 4 to 5 km in 1985 and 20 to 50 km in 1986. Additional long range TL data were derived from 1986 recordings of impulsive sounds originating from transects of a seismic survey vessel (WESTERN POLARIS) operating an array of 24 air guns.

2.2.1.1 Physical measurements

In 1985, distances and relative positions of M.V. JUDY ANN, industrial noise sources, and the AVON (during TL measurements) were obtained using the JUDY ANN's radar system. When the AVON radar return was difficult to measure at large distances due to clutter from drifting sea-ice, it was necessary to resort to measurement of the acoustic travel times of underwater impulses transmitted from the JUDY ANN and received at the AVON. Radio transmission of the received impulse time was recorded on the JUDY ANN and compared with the recorded impulse initiation time. In 1986, range information was derived using the radar system of ARCTIC ROSE and a satellite navigation system.

A standard fathometer provided depth information and navigation charts were used to estimate depth profiles along the TL paths.

Sound speed profile data were obtained through use of a Beckman Model RS5-3 Induction Salinometer which measures temperature and conductivity of the ocean water as the sensor is lowered in depth. Salinity is computed within the instrument from corresponding values of conductivity and temperature. Sound speed is calculated at discrete depth intervals using a hand calculator pre-programmed with Wilson's equation:

$$c = 1449.2 + 4.623T - 0.0546T^2 + 1.391\,(S-35)\ ,$$

where c is the sound speed in meters/second, T is the temperature (“C) and S is the salinity in parts per thousand (Urick 1983).

Wind conditions were obtained from the shipboard anemometer, and sea wave and swell heights were estimated visually. Ice cover estimates were also estimated visually.

2.2.1.2 Acoustic measurement systems

Four acoustic measurement systems were applied in this project: a primary dual channel system used for both ambient noise and industrial noise measurements, a single channel system used on the AVON during transmission loss experiments and for ambient noise and industrial noise data collection, a sonobuoy system that permitted remote measurement of ambient noise and industrial noise, and an acoustic data recording buoy for acquisition of long range transmission loss data.

Ambient and industrial noise measurement system

A standard hydrophore system that combined an ITC Type 6050C hydrophore with a low-noise preamplifier and tape-recorder was used to obtain ambient noise and industrial noise data. The hydrophore sensitivity and electrical noise-floor characteristics are shown in Fig. 3. The acoustic noise measurement system block diagram is shown in Fig. 4a. Overall frequency response of the measurement system was generally flat from 20 Hz to 15 kHz. Al 1 components of the system were battery operated during ambient and

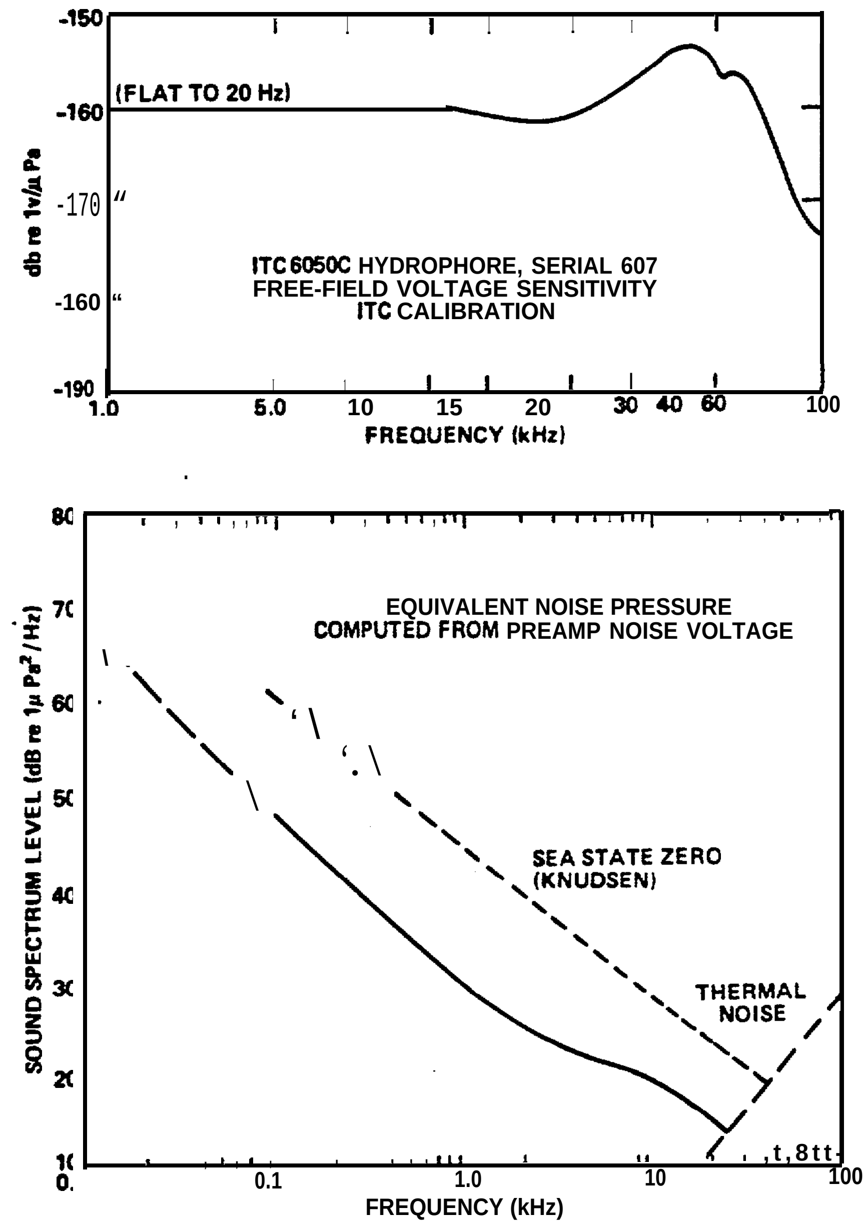


FIG. 3. MEASUREMENT HYDROPHORE CHARACTERISTICS.

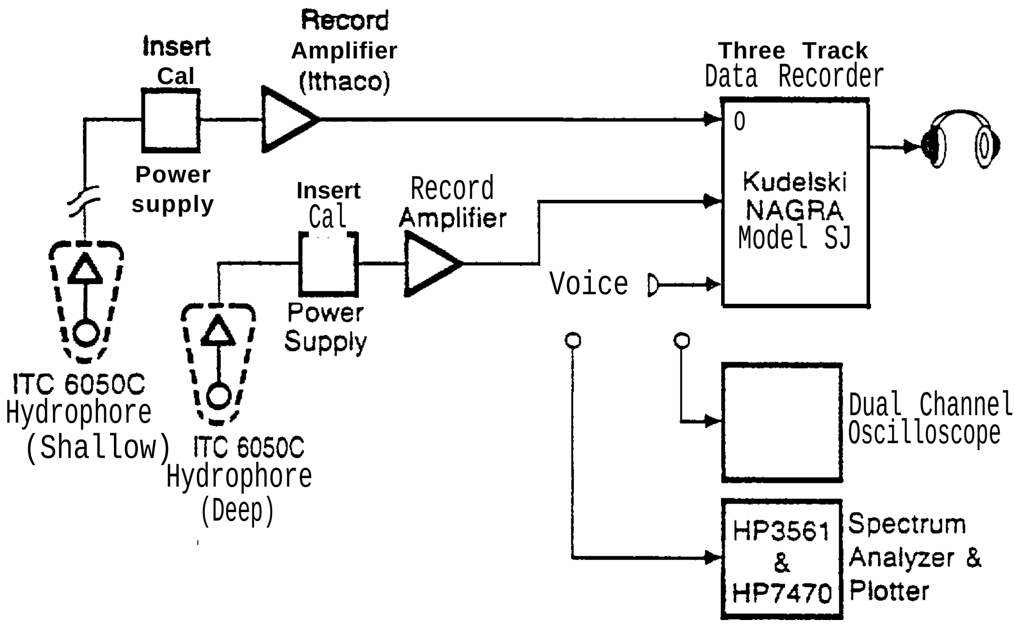


FIG. 4a: GENERAL PURPOSE ACOUSTIC MEASUREMENT SYSTEM.

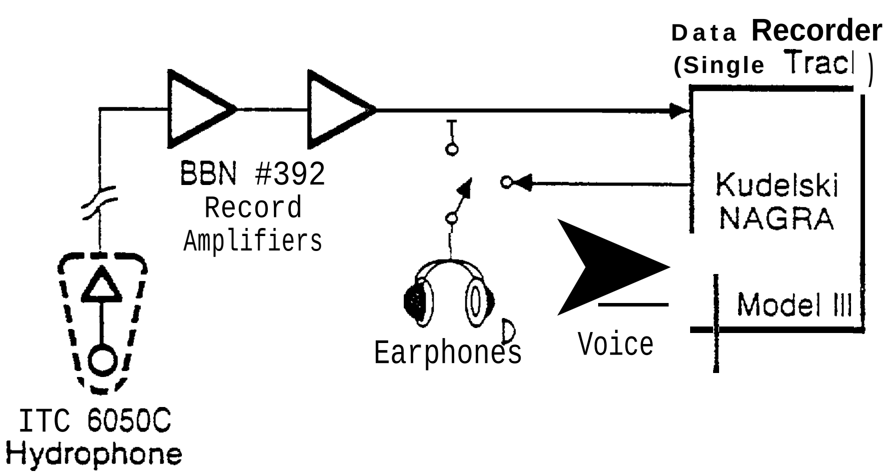


FIG. 4b. BATTERY POWERED ACOUSTIC MEASUREMENT SYSTEM FOR AVON TL MEASUREMENTS.

industrial noise measurements. Cable fairings and a support float system were used to minimize strumming and surge noise effects on the ambient measurement hydrophore. At times, particularly when recording transient sounds and industrial noise requiring wide dynamic range, it was useful to record data from a single hydrophore at two different gain settings, using both record channels. At 7.5 in. per second, the recorder has a nominal flat frequency response from 16 Hz to 16 kHz and a 60 dB dynamic range.

Single Hydrophore Receiver System (AVON)

Figure 4b provides a diagram of the single channel hydrophone system used by the second vessel (AVON). As noted, it also uses an ITC 6050C hydrophore and is compact, battery-operated, and provides the needed frequency response (30 Hz to 10 kHz at 7.5 in./sec) and dynamic range (60 dB).

Transmitting Sonobuoy Measurement System

This sonobuoy measurement system permits remote measurement of industrial noise, ambient noise, or transmission loss data, and is particularly useful when research vessel sound sources would cause contamination of the underwater acoustic data due to their proximity to a ship-mounted hydrophore. The sonobuoy electronics (a Navy SSQ57A transmitter coupled with an Edo hydrophore and Ithaco amplifier) are mounted in a 4 1/2-ft spar buoy which can either be free-drifting or moored. The frequency response of the system is flat from below 100 Hz to 10 kHz. When moored, it is often placed near an industrial site and sampled periodically during the day while the research vessel is performing other experiments or it can be used to receive acoustic transmissions during transmission loss experiments. Figure 5 is a block diagram of the sonobuoy/spar-buoy measurement system used

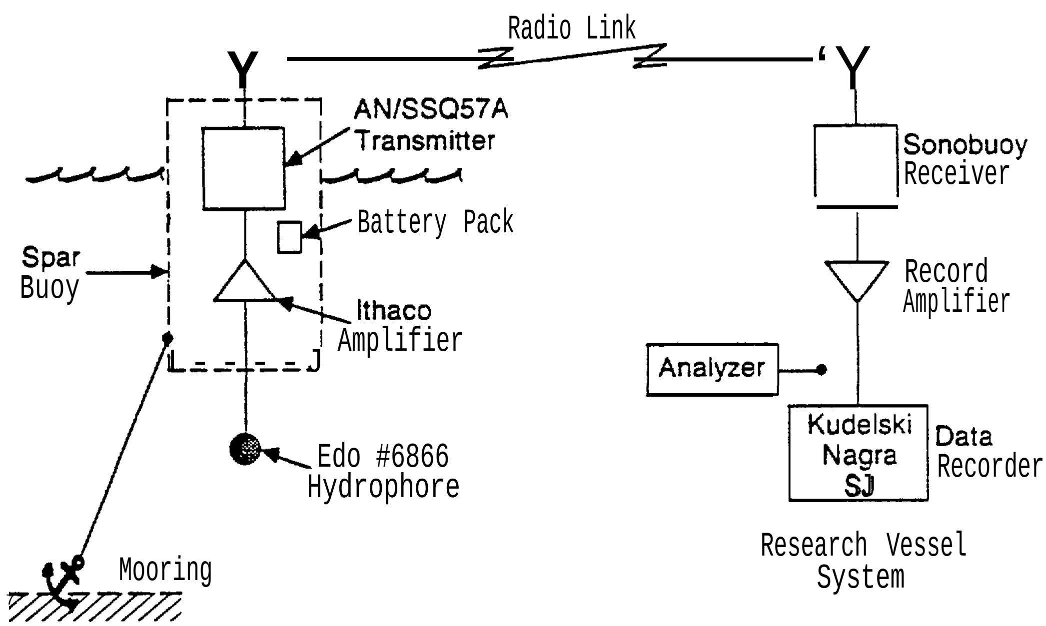


FIG. 5. TRANSMITTING SONOBUOY MEASUREMENT SYSTEM.

for this project. The buoy incorporates a high sensitivity, calibrated hydrophore, a low-noise signal preamplifier, and a sonobuoy radio transmitter. Battery life permits continuous operation for about three days. A range of about 5 km has been obtained depending on the available antenna height on the receiving vessel.

Acoustic Data Recording Buoy System

The essential element in obtaining long range TL data under this project was the assembly and use of a large spar buoy system in 1986 which provided long term recording capability and could be moored and retrieved in water up to 100-m deep. Figure 6 outlines the system. The spar buoy assembly was fabricated from 10-in. I.D. PVC schedule 40 pipe, having an overall length of 10-ft with a 6-ft mast for mounting a radar reflector and flashing beacon. The unit, which was ballasted and included a damping plate to minimize buoyant surge due to wave action, had an in-air weight of about 250-lb. The battery operated acoustic recording system consisted of a calibrated Edo Model 6866 hydrophore, a BBN Model 392 decade amplifier and a dual channel Uher Model 4400 instrumentation recorder. Each of the two record channels were calibrated with different input gains (10 dB and 30 dB) to ensure that near and distant acoustic signals from the research vessel sound system were recorded within the dynamic range of the recorder. A single TL experiment required the research vessel to deploy the buoy 20 to 40 km away from a site (e.g., to the north) and then run at full speed toward the site, stopping at specific range increments for playback of signals from the sound projector for recording on the buoy. This procedure was used to accommodate the 4-hour recording period available using the lowest 15/16 in./sec (2.4 cm/see) tape speed. The frequency response of the system was 25 Hz to 5 kHz which was compatible with the required test frequency range of 100 to 4 kHz.

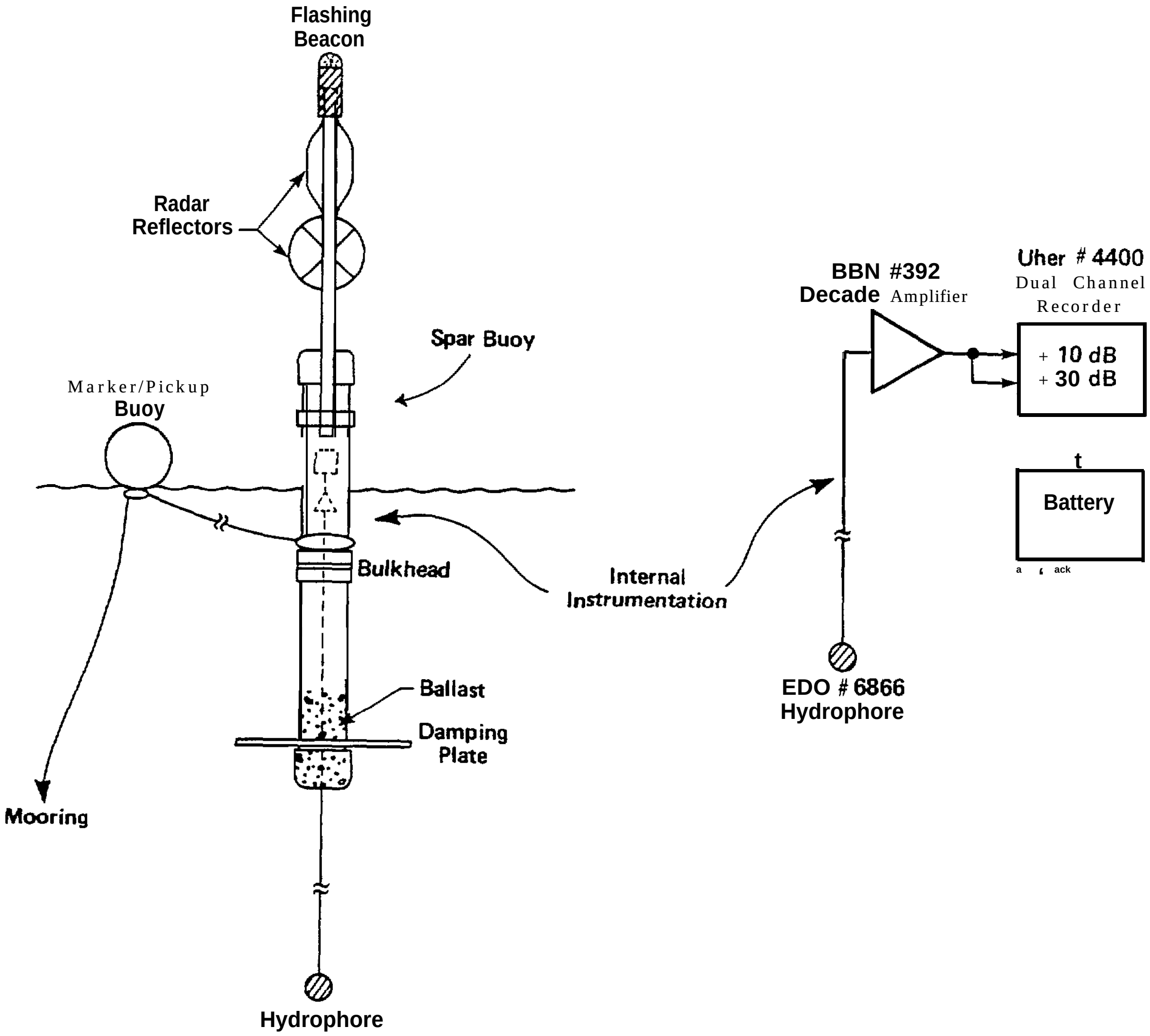
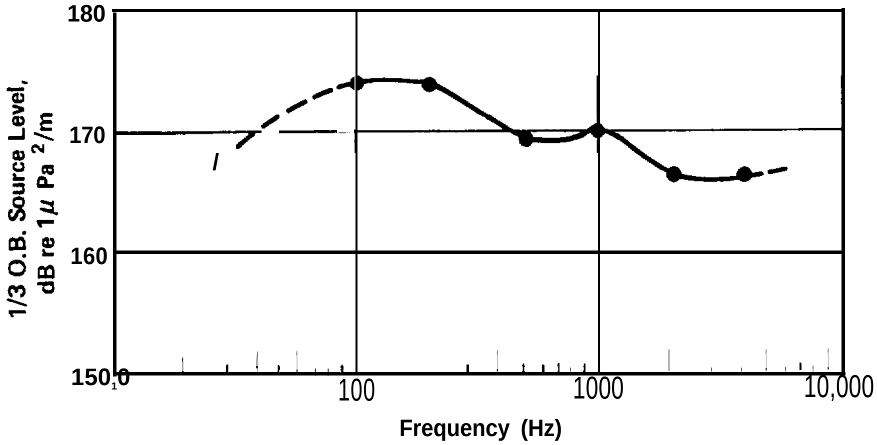


FIG. 6. ACOUSTIC DATA RECORDING BUOY SYSTEM.

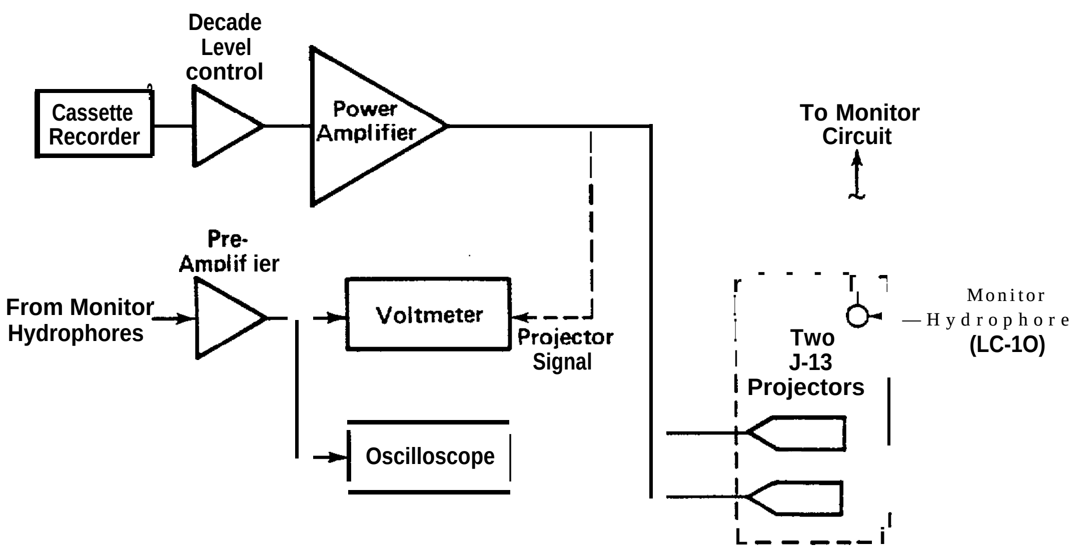
2.2.1.3 Sound projector system for transmission loss experiments

As described previously, it is necessary to determine the site-specific characteristics of sound propagation from the selected industrial sites. To accomplish this, a sound source with known frequency and sound level characteristics must be located near a site and the level of the controlled radiated signal measured as a function of distance from the source. If an industrial source radiates sounds in a continuous or invariant manner, that industrial source can be used as the "transducer". Recording that continuous sound as a function of distance provides the needed TL data. However, industrial sources rarely produce invariant sounds. Hence, a calibrated source of known characteristics is a more useful alternative. The industrial noise spectrum of interest to this project is primarily low frequency in character, mostly concentrated below 1 kHz (e.g., Greene 1985). Since some energy is encountered occasionally in the 1 to 4 kHz region, it was decided that a single standard U.S. Navy J-13 sound projector would suffice for the expected 1985 field measurement conditions. It was determined that a pair of J-13 transducers would be needed in 1986 to obtain needed long-range transmission loss data. Figure 7 provides a plot of the" one-third octave band sound levels,* referenced to l-meter distance, which were used during the 1986 experiments with a pair of J-13 transducers. A block diagram of the sound projector system used is also included. The J-13 projectors were calibrated by the U.S. Navy Underwater Sound Reference Division of the Navy Research Laboratory. In order to maintain continuity from one experiment to the next, a series of 1/3 octave band

*One-third octave band levels represent the acoustic energy existing within discrete frequency bands which have a width of 23% of the center frequency and are spaced at one-third octave intervals, See Appendix F-for a list-of standard one-third octave band center frequencies.



J-13TRANSDUCER PAIROUTPUTSIGNAL LEVEL



PROJECTOR
INSTRUMENTATION

FIG. 7. J-13 SOUND PROJECTOR SYSTEM AND ONE-THIRD OCTAVE BAND SOUND LEVELS USED IN TRANSMISSION LOSS EXPERIMENTS.

tones and pulses from 100 Hz to 4 kHz were recorded on a cassette tape. The output of that tape was amplified and adjusted for consistent and repeatable drive signals to the J-13 projector. As shown, the acoustic output of the J-13 was monitored continuously with an LC-10 hydrophore. The J-13 transducers mounted in a frame were suspended over the side of the research vessel and operated with the vessel free drifting (engines off) at each selected TL station. The vessel was not anchored for these measurements because of the potential for damage by drifting ice and because the water depths at some sites (Hammerhead, Erik, Belcher, and Corona) were beyond the anchoring' capability of the research vessel. Work with the data recording buoy involved mooring the buoy and then moving the research vessel away from the buoy on a radial course from a site stopping at pre-selected positions to deploy the J-13 system for the playback of pre-recorded 1/3 octave band tones and pulses. The procedure was repeated for 6 or more range increments until the full 20 to 24 km radial had been completed.

Since the variation of sound speed with depth is important to the interpretation of the" measured transmission loss (TL) data, the sound speed profile was determined at regular intervals with the Beckman salinometer at each site, not only before and after the TL experiments but at the time of measuring ambient noise segments and industrial noise signatures.

2.2.2 Analysis of acoustic data

Recorded on ambient noise, industrial noise, and underwater sound propagation data were analyzed to provide a quantitative definition of the underwater acoustic environment in the Beaufort Sea OCS planning area. The analysis format was selected to be compatible with the requirements of the “zone of influence” assessment to be performed by LGL Ltd. For example, the emphasis on third octave data in this report is a result of data requirements for the 'zone of influence' assessment (see Section 2.3.1). The analysis procedures and results used by LGL are described in Section 2.3, and Section 3. The methods used in analysis of the acoustic data are described below, the results of which are provided in Section 3.

2.2.2.1 Ambient noise analysis

The objective of the ambient noise measurement and analysis effort is to develop a statistical description of the variation of the underwater background noise conditions at each of the selected sites. Ideally this should include long-term measurement of noise conditions as a function of time of day, month, and season to permit a complete statistical description. For practical reasons, this project was limited to collection of short-term samples of the ambient noise field during two 30 to 35-day periods. This results in an incomplete description of the ambient noise condition for the sites of interest. In order to estimate the noise statistics over a wider range of conditions and times, additional analysis was done using published wind and ice data for the North Slope area to supplement the summertime measurements, resulting in noise statistics over a wide range of conditions and times.

The 5th, 50th, and 95th percentile levels of the site-specific ambient noise statistics were estimated on a l-Hz band basis as well as for one-third octave bands spanning the frequency range of interest. Typically, estimates were derived for 1/3 octave bands centered at 100, 500, and 2000 Hz. However, this was not always possible. For instance, at Orion in 1985 there were interfering tonal sounds at 2 and 4 kHz, so we analyzed noise statistics at that site for bands centered at 100, 500, 1000, and 3000 Hz.

The data analysis procedure employed was as follows. The analog tape recordings were passed through a signal conditioner and then through a one-third octave band filter set at the desired frequency. The amplitude envelope of the band limited signals was then defined by using a logarithmic amplifier and a 10 Hz low pass filter. A spectrum analyzer (Hewlett Packard Model 3562), was used for for histogram generation and calculation of the cumulative distribution function (CDF) of these signals. Figure 8 is a block diagram of the data analysis system. Average narrowband power spectra were also developed to provide a general overview of the noise characteristics.

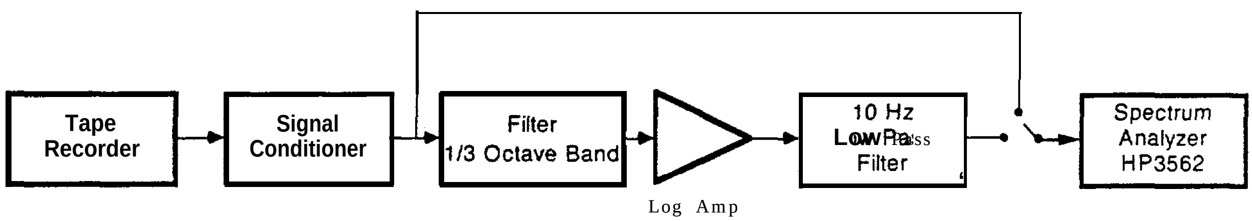


FIG. 8. AMBIENT NOISE DATA PROCESSING SYSTEM.

From the CDFS, three ambient noise levels were collected: the level below which the third octave band noise remained 95% of the time, the median (50th percentile) noise level and the level below which the noise occurs 5% of the time. The data samples were relatively short (3 to 5 minutes) since the goal was to characterize the site-specific noise statistics at the times we occupied the site. Ambient noise data were selected for analysis when seismic survey pulses were absent.

Ice cover and wind statistics for the Beaufort Sea regions of interest to this study were obtained from a recent NOAA publication (Brewer et al. 1977) and the Alaska Marine Ice Atlas, AEIDC, University of Alaska (LaBelle et al. 1983). The atlas data were used together with reported shallow water ambient noise data to derive long-term ambient noise statistics for the September-October period in the test areas. The procedure involved combining the cumulative probability distributions of sea-state and ice-cover conditions in the test areas to determine the 95th, 50th, and 5th percentile effective conditions. Shallow water ambient noise data for the Beaufort Sea obtained by this study, as well as data reported by Greene (1985), Moore et al. n.d. [1984], and Urick (1985 p. 225), were examined to synthesize spectra corresponding to the required 95‘h, 50th (median), and 5th percentile conditions. The resulting 95‘h, 50th, and 5th percentile ambient 1/3 octave band level estimates were provided to LGL for their use in estimating zones of potential noise influence.

Ambient noise data recorded in 1986 were analyzed in sufficient detail to determine that the 1986 natural background noise levels fell within the 5th and 95th percentile statistical limits published in the interim report on the 1985 field season results. Those data, together with the 1985 ambient noise statistics, are provided in Section 3.1.

2.2.2.2 Industrial noise analysis

The objective of the industrial noise measurement and analysis effort was to determine the source levels of dominant frequency components of underwater noise related to industrial operations. The 1985 and 1986 field season measurements produced a reasonable sample of typical industrial noise existing during the summer in the Alaskan Beaufort region. The analysis procedures used on the available data are described below.

The analog recordings of ambient noise and industrial noise obtained in the field were played back into a spectrum analyzer and average power spectra were obtained. The durations of these averages varied depending on the noise source but typically were on the order of 1 to 2 minutes. Time segments were selected which were not influenced by seismic pulses. The spectra were corrected for system gains and hydrophore sensitivities to permit presentation of the data in terms of absolute received sound levels as a function of frequency. These calibrated levels were then compared to ambient noise measurements taken at the specific sites to establish data validity in terms of acceptable signal-to-noise ratio. Narrowband tonals and broadband components that exceeded the ambient noise spectra were assumed to be due to the industrial activity.

In some cases, where measurements were made at various ranges, the noise components were examined as a function of range. Those which disappeared at short ranges are typically ignored in this analysis. (For example, the 90 and 100 Hz tonals observed during drilling at the Sandpiper site, discussed in Section 3.2.5 of the 1985 field season report, Miles, et al. 1986) .

The final step in the analysis was to correct the received levels for the site-specific transmission loss (TL) characteristics to provide spectra in terms of radiated noise source level referred to a standard reference distance of 1 meter. In working with the 1985 data, for instance, independent measurements of TL at the Erik site were used to derive source level estimates, corrected to a 1 m reference range for the two industrial activities at that site. For the Hammerhead data, no TL measurements with a calibrated invariant source were available in 1985, requiring the initial use of the industrial noise itself (McLaren et al., 1986) to estimate the local site-specific TL characteristics. Transmission loss at Hammerhead was measured directly in 1986 (Table 3). The drilling activity at Sandpiper Island posed another problem. Although we had measured the TL characteristics, the environmental conditions had included 1/10-2/10 ice cover at the time. The Greeneridge Sciences drilling noise data (Johnson et al. 1986) were acquired later, with 8/10-10/10 ice cover. Since ice cover directly influences the sound transmission loss characteristics, rather than use potentially inappropriate TL estimates, the actual radiated noise measurements were used to estimate the site-specific local TL characteristics. The resulting data were used to adjust the 1985 Sandpiper noise spectra to l-meter source levels.

The results of the analysis of industrial noise appear in Section 3.2.

2.2.2.3 Transmission loss data analysis

Sound propagation data were acquired and analyzed to determine the dependence of received level on the range from a calibrated source. Warble tones with a 1/3 octave bandwidth were projected in a sequence with center frequencies of 100, 200, 500, 1000, 2000, and 4000 Hz. Received sound levels of these controlled tones were measured at discrete distances from the sound projector. Measurements were made to determine the sound speed profile at each of the test sites. This information was used to select the sound source and receiving hydrophore depths for the TL measurements. Generally depths of 10 to 12 m were used for both the source and the receiving hydrophore. These depths were below most observed surface layer effects and representative of mid-depth conditions. The tape recordings of each warble tone for each distance increment were played through a decade amplifier into a Hewlett Packard Model 3561A Dynamic Signal Analyzer which provided a sound level vs frequency spectrum of each signal being analyzed. Tabulation of the resulting received sound levels at each of the above center frequencies as a function of distance from the source provides the basis for plotting the transmission loss characteristic for each specific transect investigated.

Most TL data were obtained using the J-13 sound source on the research vessel and the receiver at the Acoustic Data Recording Buoy (1986) or on an inflatable boat (1985), as described earlier. This system provided useful TL data out to distances of 4-5 km in 1985 and out to about 20-24 km in 1986, as determined by the recording tape capacity in the buoy.

The derivation of TL information for distances beyond 20 to 24 km in 1986 relied on recordings of seismic survey impulses originating at the Western Geophysical vessel WESTERN POLARIS. Western Geophysical cooperated with this project by providing information which allowed us to derive air gun array (WESTERN POLARIS) distance from our receiver on M.V. ARCTIC ROSE as a function of time. Their survey operations proceeded uninterrupted during the BBN acoustic measurement work and only segments of those transects run in the vicinity of the selected sites were recorded at regular time intervals. Analysis of the recorded impulses provided water-path acoustic transmission loss data for distances of 4 to 40 km between the two vessels. The seismic array consisted of 24 air guns which were towed at a depth of 6.1 m and had a total volume of 1750 cubic inches operating with an air pressure of 4500 psi. The air guns were fired at intervals of approximately 10 seconds.

The tape recorded seismic array impulses were processed through a Hewlett Packard Model 3561A signal analyzer set up in the peak-hold mode. A series of three adjacent impulses were captured and the maximum root-mean-square impulse level derived for each 1/3 octave band from 16 to 315 Hz (the overall bandwidth containing most of the seismic impulse energy from an air gun array). The HP 3561A also provided plots of impulse signal amplitude vs time. This analysis procedure was applied to the recorded impulses at each range increment recorded during each transect of interest. Typical elapsed time between the beginning and end of a survey transect segment recorded for TL purposes was about six hours.

The results of the transmission loss data reduction procedure consists of tables of received level versus range for each test frequency. These tables were used in a computer-implemented procedure to fit a semi-empirical transmission loss model to the data using the method of least-squares (see Section 3.3.2). The model, based on an analysis by Weston (1976), provides for propagation following a spreading loss characteristic appropriate for the site-specific local conditions. In the process of fitting the model to the data, values of a bottom loss parameter and a local transmission anomaly factor are determined. This permits the model to be used for prediction of transmission loss to ranges extending well beyond the limits of the measured data. The procedure is discussed in Section 3.3.

2.3 Whale Behavioral Response Analysis Methods*

To estimate the radius from a specific industrial site within which whales will react to its underwater sound, two main types of information are needed: (1) measurements or predictions of the levels of industrial noise at various distances from the site, and (2) information about the responsiveness of whales to varying sound levels. Previous studies have obtained consider-

*By W. John Richardson, LGL Ltd., environmental research associates.

able information about the characteristics of industrial sounds from oil industry activities in the Beaufort Sea (e.g., Ford 1977; Malme and Mlawski 1979; Cummings et al. 1981a,b; Greene 1983, 1985; Moore et al. n.d. [1984]; Davis et al. 1985; Ljungblad et al. 1985b; Johnson et al. 1986; McLaren et al. 1986). However, only a minority of these data came from the specific sites where the Alaskan oil industry is drilling or planning to drill. Similarly, most of the available data on reactions of bowhead whales to oil-industry activities, and all of those for gray whales, came from locations different from those where drilling is now underway or planned in the Alaskan Beaufort Sea. A central objective of this project is to obtain the site-specific data that are necessary, along with existing non-site-specific data, to estimate zones of potential noise influence for various industrial activities at several specific sites in the Alaskan Beaufort Sea.

The type of industrial activity at a given site will affect the size of the predicted zone of influence because different industrial activities result in sounds with differing source levels and frequency composition. Furthermore, the size of the zone of influence for a given industrial activity will depend on the location of that activity because propagation conditions differ among sites. Thus, separate zone of influence analyses are needed for each combination of industrial activity and site. A further complication is that, at locations where water depth or bottom composition are different on different bearings, the zone of influence is likely to extend farther in some directions than in others.

It is impractical to conduct propagation experiments to measure received sound levels for each potentially relevant combination of site, bearing, and type of industrial sound. It would be even more impractical to test the reactions of whales to all of these combinations. The approach used in this study has been to determine the levels and frequency characteristics of the sounds emitted by the key types of industrial activity, measure sound propagation characteristics at each site of interest, and develop site-specific models that predict received sound levels as a function of source level, frequency, distance and bottom slope (i.e., bearing). These models can then be used to make site-specific estimates of received levels of sounds from any industrial activity that might occur at that site, provided that its source level and frequency characteristics are known. Zones of potential influence can then be estimated, to a first approximation, by relating these acoustic results to behavioral data from previous studies of the responsiveness of whales to various types and levels of industrial sounds.

2.3.1 Definition of zone of influence

Noise can affect animals in several different ways, at least in theory. The sizes of the zones of audibility, responsiveness, masking, and hearing damage will differ greatly (Richardson et al. 1983). When the noise level is extremely high, discomfort or permanent damage to the auditory system is possible (Kryter 1985). Industrial noise levels high enough to cause auditory damage would be expected to be restricted to relatively strong noise sources and to relatively close distances. Auditory damage would not occur at any distance unless the source level of the noise was quite high. Thus the zone of auditory damage is expected to be small or absent. At the other extreme, the behavior of an animal might be affected, at least subtly, at any distance where the industrial noise was audible. The zone of audibility would be much larger than that where auditory damage is possible. The zone of influence of a noise source might also be defined as the area where animals respond overtly by avoidance or some other alteration in behavior. This zone of responsiveness might, in theory, be as large as the zone of audibility if animals responded to any industrial sound that they could hear. However, it might also be considerably smaller than the zone of audibility if animals responded only to industrial sounds that exceeded a specific absolute level, or to sounds that exceeded the detection threshold by some minimum amount. Still another possibility is a zone of masking, which would be the area within which the ability of an animal to hear important environmental sounds, calls from other members of its own species, etc., would be impaired by the masking effect of industrial noise.

The size of the estimated zone of influence around an industrial site will vary greatly depending on the definition of zone of influence that is used. The following subsections review the major factors known or suspected to affect the sizes of the zones of audibility, responsiveness and masking. These subsections provide the justification for some of the procedures that we have applied in this study. These sections deal primarily with sources of continuous or near-continuous noise, which are the primary topic of this study.

Zone of Audibility. -- This is the largest of the zones of possible influence. The radius of audibility will depend partly on the source level of the industrial noise and on its rate of attenuation with increasing range. However, the size of this zone will also depend on the ambient noise level and the minimum ratio of industrial noise to ambient noise that can be detected. This ratio is often taken to be 0 dB, i.e., assuming that a sound can be detected provided that it is no less intense than the background noise at corresponding frequencies. However, in some circumstances sounds can be detected even when they are somewhat less intense than the background noise, i.e., at a signal-to-noise ratio slightly less than 0 dB (see Richardson et al. 1983 for review). Another consideration is the absolute hearing sensitivity of the animal. If the absolute detection threshold is above the ambient noise level, then the zone of audibility will be limited by detection threshold, not ambient noise.

Any attempt to estimate the zone of audibility of a sound to bowhead or gray whales is hampered by the fact that there have been no measurements of the hearing thresholds of any baleen whales. Baleen whales communicate with one another by calls at low to moderate frequencies (Thompson et al. 1979; Clark 1983). Most bowhead calls are at frequencies 50-500 Hz, but some calls contain energy up to 5000 Hz (Ljungblad et al. 1982; Clark and Johnson 1984; Cummings and Holliday 1987). It seems safe to assume that whales are sensitive to the frequencies contained in their calls; there is behavioral evidence that some baleen whales detect and respond to calls from conspecifics many kilometers away (Watkins 1981; Tyack and Whitehead 1983). The structure of the hearing apparatus of baleen whales is appropriate for detection of low and moderate frequencies (Fleischer 1976; Norris and Leatherwood 1981). Malme et al. (1983) demonstrated that migrating gray whales could detect the presence of Orca (killer whale) sounds in a tape playback experiment when the signal-to-noise ratio was about 0 dB.

Payne and Webb (1971) pointed out that, at 20 Hz, detection range would be limited by background noise rather than auditory sensitivity even if auditory sensitivity were as much as 30 dB poorer than human auditory sensitivity at humans' most sensitive frequency. Thus, following Payne and Webb (1971) and Gales (1982a,b), we assume that ambient noise, not limited auditory sensitivity, sets the upper limit on the zone of audibility.

In estimating the zone of potential audibility, another factor that must be considered is the "critical bandwidth" around each frequency. The critical bandwidth is the range of frequencies within which background noise affects the ability of the animal to detect a signal. To a first approximation, critical ratio (in dB) is equal to 10 log (critical bandwidth). Here we are concerned with the detection of an industrial sound signal in the presence of natural background noise from wind, waves, ice, etc. In those mammal species that have been studied, the only background noise that has a significant effect on detection of a sound signal is the noise within a band roughly 1/3 octave wide, centered at the frequency of the sound signal (Fig. 9; Popper 1980; Gales 1982a,b). A l/3-octave band around any frequency x extends from

$$x*2^{-1/6} \text{ to } x*2^{1/6}$$

i.e., from 0.891x to 1.122x. The width of a l/3-octave band is 23% of the center frequency. For example, the l/3-octave bands around 50, 500 and 5000 Hz are approximately 45-56, 450-560, and 4500-5600 Hz, respectively.

Critical, bandwidths have not been determined for any baleen whale, but the l/3-octave "rule of thumb" seems to be a good first approximation for in-air and in-water hearing by a variety of mammals and even fish (Fig. 9). Again following Payne and Webb (1971) and Gales (1982a,b), we have assumed that the critical bandwidth is 1/3 octave. (Gales also considered a wider bandwidth when the frequency was <450 Hz.) It should be noted that signal-to-noise ratios for many industrial sounds relative to ambient noise do not depend strongly on the bandwidth chosen for analysis. Industrial noise as well as ambient noise is at least partly broadband in character. In this situation, if a bandwidth wider or narrower than 1/3 octave is chosen, the industrial and ambient noise levels will increase or decrease more or less proportionately, and the signal-to-noise ratio may not change much.

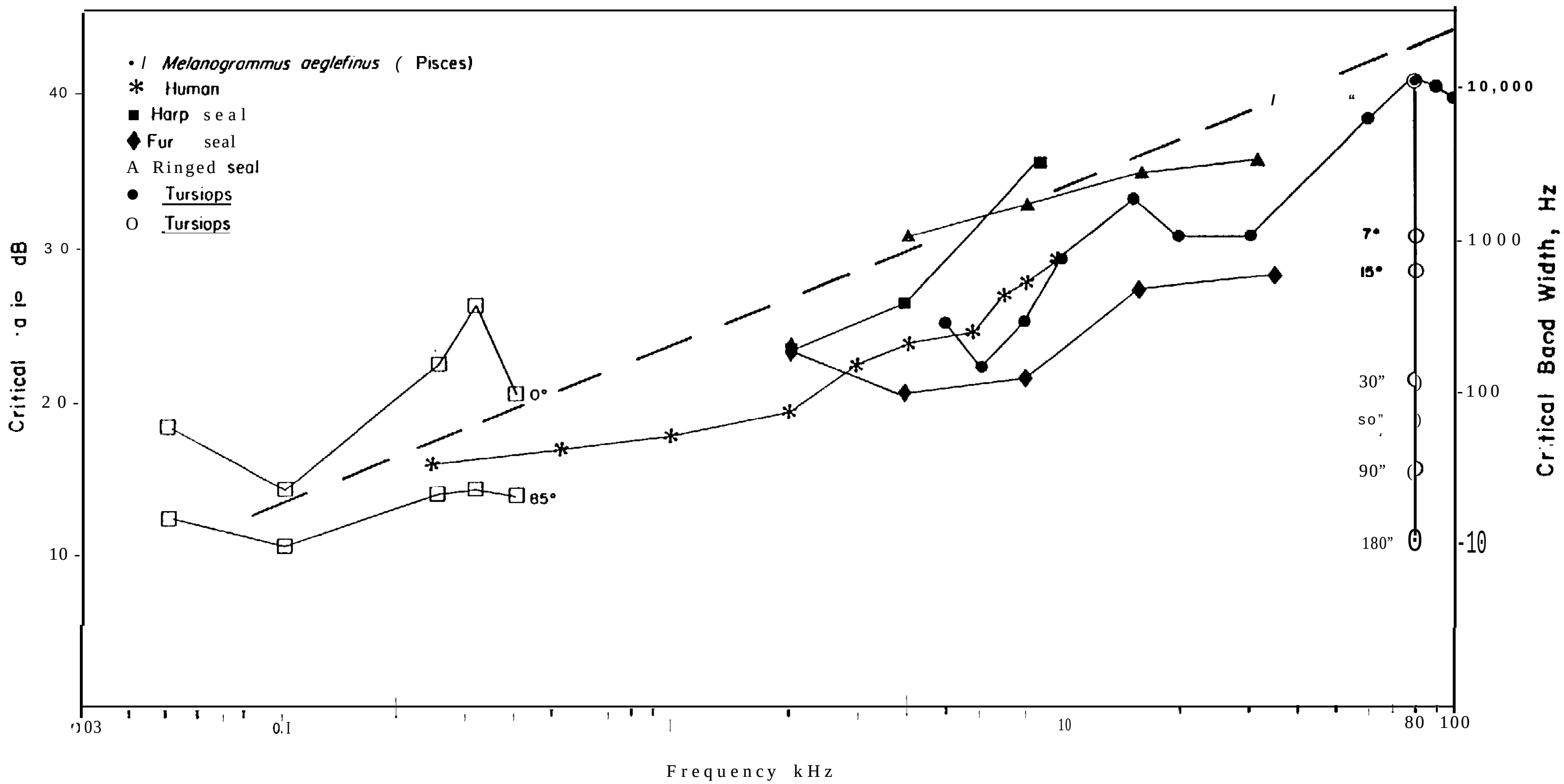


FIGURE 9. CRITICAL RATIOS AND ASSOCIATED CRITICAL BANDWIDTHS OF SEVERAL MARINE MAMMALS, MAN, AND HADDOCK. DASHED LINE REPRESENTS 1/3 OCTAVE. CRITICAL RATIOS FOR THE BOTTLENOSE DOLPHIN (*Tursiops*) AND HADDOCK ARE KNOWN TO DEPEND ON THE ANGULAR SEPARATION BETWEEN SIGNAL AND NOISE SOURCES (SEE OPEN SYMBOLS). SOURCES ARE CHAPMAN (1973) FOR HADDOCK, HAWKINS AND STEVENS (1950) FOR HUMAN, TERHUNE AND RONALD (1971) FOR HARP SEAL, MOORE AND SCHUSTERMAN (1987) FOR FUR SEAL, TERHUNE AND RONALD (1975) FOR RINGED SEAL, AND JOHNSON (1968) AND ZAYTSEVA ET AL. (1975) FOR *Tursiops*. MODIFIED FROM RICHARDSON ET AL. (1983).

The directional hearing abilities of baleen whales are unknown. In theory, if they can determine the direction from which a sound signal (e.g., industrial noise) is arriving, they might be able to detect it even at a signal-to-noise ratio well below 0 dB. An ability to detect a sound in the presence of much noise is in some respects equivalent to having a very narrow critical bandwidth. The sound detection ability of dolphins has been shown to depend strongly on the relative directions of the signal and noise sources, at least at high frequencies (Fig. 9). The directional effect is not expected to be as great at low frequencies because of the longer wavelengths and, in shallow water, because of the complex interactions of the sound with the bottom and surface. On the other hand, the large size of baleen whales may partly compensate for the long wavelengths of the dominant industrial sounds. Following Payne and Webb (1971) and Gales (1982a,b), we have assumed that baleen whales do not gain any increased auditory sensitivity through directional hearing.

Payne and Webb (1971) provided the first comprehensive attempt to estimate the zone within which a baleen whale could detect a particular sound. Their analysis concerned the range to which fin whales in deep water might detect the intense 20-Hz calls made by other fin whales. However, the principles described in their paper are equally relevant to the detection of industrial sounds, many of which are predominantly at low frequencies. Payne and Webb showed that, in certain deep-water situations, the intense calls of fin whales might be detectable hundreds or even thousands of kilometers away. The source levels of fin whale calls, about 180 dB re 1 μPa at 1 m, are not dissimilar to source levels of some industrial sounds. Thus, the zone of audibility might be very large in some situations. (As will be discussed later, the zone of audibility of low frequency sounds is expected to be much smaller in shallow water, such as that near drillsites on continental shelves.)

The first detailed attempt to estimate the zone of audibility of underwater sounds from an oil industry activity involved noise from proposed icebreaking Liquefied Natural Gas "tankers" (Peterson [cd.] 1981). To estimate the expected source levels and frequencies, theoretical models and measurements from existing large ships were considered (e.g. , Leggat et al. 1981) . Existing data on propagation losses within the proposed operating area were used, along with existing ambient noise statistics (Leggat et al. 1981; Verrall 1981). It was tacitly assumed that marine mammals would be able to hear ship noise if its received level was above the ambient noise level at corresponding frequencies. It is noteworthy that many of the data and analyses used in this assessment came from naval investigations, only a minority of which have been reported in the open literature. Data on sound propagation and background noise in some other areas of interest to the oil industry are undoubtedly available in restricted sources.

Gales (1982a,b) estimated zones of audibility around a semi-submersible drilling rig and two fixed drilling platforms. His estimates were based on measurements of sound levels and spectral characteristics near the industrial sites, along with a series of alternative assumptions about propagation losses (spherical vs. cylindrical) and ambient noise (low, moderate and high). Gales made the same types of assumptions about baleen whale hearing as were made by Payne and Webb, with one elaboration: Gales considered the possibility that the critical bandwidth for low frequencies is wider than 1/3 octave. Gales concluded that noisy platforms radiate low frequency underwater sounds that could be audible at ranges "on the order of hundreds of miles" under favorable conditions of propagation and ambient noise. However, under unfavorable conditions, i.e., poor propagation and high ambient noise, even the noisiest platforms might be detectable only within ranges "of the order of 100 yards". Estimated ranges of audibility differed by factors of 10-1000 depending on the assumed propagation conditions and ambient noise levels.

Gales (1982b) concluded that accurate site-specific predictions of detection range will require data on (1) the acoustic source spectrum for the particular industrial source of interest, (2) propagation conditions for the particular location and season, and (3) ambient noise under the specific conditions of interest. Gales also suggested that it would be important to consider the particular species of animal involved as listener. However, in the case of baleen whales, species-specific predictions of the zone of audibility will not be possible until something is learned about the relative auditory capabilities of different baleen whales. If their hearing abilities are limited by ambient noise rather than auditory sensitivity, as is expected, then the zone of audibility is not expected to differ appreciably among species of baleen whales.

In shallow waters where most oil industry activities take place, the zone of audibility is expected to be restricted by the greater rate of attenuation of underwater sound in shallow water. Before this project there had been no specific estimates of the zone of audibility around oil industry sites in the Beaufort Sea, although several studies had provided measurements of received sound levels at various distances from such sites.

<u>Zone of Responsiveness</u>. -- Gales (1982a,b) emphasized that the zone of influence should be estimated based on the noise levels that cause whales to react overtly. However, when his analyses were done, there was little specific information about the noise levels that would and would not elicit responses from baleen whales. Consequently, Gales could only estimate zones of potential audibility, not zones of responsiveness.

Reactions of several species of baleen whales to more-or-less continuous underwater sounds from industry have been studied intensively in recent years. Richardson and Malme (1986)--Appendix B in Miles et al. (1986)--summarized the data concerning reactions of bowhead and gray whales to drilling and island construction sounds. To assist in interpreting the bowhead data, that report also included previously unreported industrial noise data on a 1/3-octave band level basis (unpubl. noise data from C.R. Greene, compiled by LGL). With the data that are now available, we can make at least rough estimates of noise levels that do and do not elicit responses from bowhead and gray whales. For gray whales, the data are from Malme et al. (1983, 1984, 1986). For bowheads, the behavioral data are from Richardson et al. (1985b,c), and the noise data are from Greene (1985 and unpubl.).

The studies mentioned above provided some direct indications about the ranges from industrial sites at which reactions were observed. However, the studies were not done at the specific sites in the Alaskan Beaufort Sea where drilling is occurring or planned. Hence, the zones of responsiveness determined in the previous studies provide only an indication of the likely zones of responsiveness at any particular site. Sound propagation phenomena at the site of interest must be taken into account before the previously-available data can be translated into site-specific estimates of zones of responsiveness.

Whales might, in theory, react to underwater industrial noise at any range where it is audible. If so, the zone of responsiveness would be the same as the zone of audibility. However, the recent studies of bowhead and gray whales, and less detailed observations of some other species of baleen whales, indicate that whales often are seen within areas ensonified by industrial activities. In the Canadian Beaufort Sea during summer, numerous bowheads have been seen to engage in seemingly-normal activities within several kilometers of drillships or dredges, where the broadband industrial noise level was up to 114 dB re 1 μPa, or 16 dB above the average ambient level. In these cases, noise levels in the l/3-octave band of maximum signal-to-noise ratio were up to 105 dB re 1 μPa, or 29 dB above average ambient (Table 4C,G). A few individual bowheads have been seen by biologists at locations with even higher noise levels--on a broadband basis, 127 dB re 1 μPa or about 29 dB S:N, and on a l/3-octave basis 117 dB or 41 dB S:N (Table 4B,D,F; Fig. 10,11--data from Richardson et al. 1985b,c). Details about the occurrence of bowheads in these situations were reviewed by Richardson and Malme (1986).

Noise playback experiments have also indicated that some bowheads show no detectable reaction to broadband noise up to at least 20 dB above ambient levels (Table 5A). On the other hand, some other bowheads show avoidance reactions (orient and move away) when drillship or dredge noise* is received at broadband levels as low as about 10 dB above ambient (Table 5B,C; Fig. 10). Again, corresponding figures for the l/3-octave band of maximum noise were higher--some bowheads avoided at S:N levels as low as 16 dB, whereas others showed no detectable reaction at S:N levels as high as 38 dB (Table 5; Fig. 11).

*The noise projected into the water during the drillship playback experiments was recorded by Greene (1985, 1987) 0.2 km from drillship EXPLORER II in 1981, and undoubtedly was dominated by sound from the drillship *per se*. This drillship recording was used for both LGL's playbacks near bowheads and BBN's playbacks near gray whales. The noise projected during LGL's 'dredge' playback experiments near bowheads was recorded 1.2 km from the suction dredge BEAVER MACKENZIE in 1980. This recording included composite sounds from the dredge and support vessels. LGL's playbacks all consisted of a 10-13 min period when sound level was increased gradually (to avoid a sudden onset of sound at peak level), a 10-20 min period at peak level, and a 10 min period of gradually decreasing level.

Table 4. Estimated noise levels (dB re 1 µPa) at locations where bowhead whales have been seen near drillships and dredges.***

	Range (km)	20-1000 Hz (dB) Rcvd Lev.	20-1000 Hz (dB) Avg. Amb.	20-1000 Hz (dB) Approx. S:N	1/3-Oct. Band (dB)* Rcvd Lev.	1/3-Oct. Band (dB)* Avg. Amb.	1/3-Oct. Band (dB)* Approx. S:N
EXPLORER drillships							
A. Closest ind. rep.**	0.2	135	98	37	132	78	54
B. Closest biol. "	4	118	"	20	112	"	34
C. Whales numerous at	13	104	"	6	93	"	15
KULLUK Conical. Drilling Unit							
D. Closest biol. rep.**	10	117	98	19	104	74	30
BEAVER MACKENZIE suction dredge							
E. Closest ind. rep.**	0.1	137	98	39	127	76	51
F. Closest biol. "	0.8	127	"	29	117	"	41
G. Whales numerous at	5	114	"	16	105	"	29

*1/3-octave band with maximum signal-to-noise ratio; band centered at 250 Hz for EXPLORER, 630 Hz for KULLUK, and 400 Hz for BEAVER MACKENZIE.

**Closest reports by industry personnel and by biologists are shown.

***Received levels are based on equations fitted to Greene's (1987) measurements of received level vs. range from these three sources (see Richardson and Malme 1986, p 231, for equations). The "Approximate Signal-to-Noise Ratio" column assumes that ambient noise was near average (as determined by Greene 1987) when the whales were seen; actual ambient noise levels could not be measured in these situations because of the presence of stronger industrial noise.

Table 5. Noise levels and signal-to-noise ratios during playbacks of drillship and dredge noise near bowhead whales (based on Richardson et al. 1985c and unpublished data). These same data are shown graphically in Figure 10 (broadband) and Figure 11 (1/3-octave band). Source level, ambient level, and received level at sonobuoy were measured; received levels at other ranges were estimated, as were the ranges from the actual drillship or dredge at which these levels would be received (see Richardson and Malme 1986 for details). All levels are in dB re 1 µPa.

			20-1000 Hz Band				Max I/s-Octave Band*			
	Source Level (dB)	Range (km)	Amb-ient (dB)	Rcvd Lev., Peak Plbk (dB)	S:N, Plbk: Amb. (dB)	Equiv Range From Ship (km)	Amb-ient (dB)	Rcvd Lev., Peak Plbk (dB)	S:N, Plbk: Amb. (dB)	Equiv Range From Ship (km)
A. Drillship Playbacks--No Avoidance										
18 Aug 82	164									
Sonobuoy		2	97	110	13	9.0	79	108	29	5.7
Closest Bhd		3	"	107	10	11	"	105	26	7.0
Farthest Bhd		6.5	"	100	3	16	"	96	17	11
22 Aug 83	164									
Sonobuoy		1.2	93	113	20	7.1	75	111	36	4.5
Closest Bhd		.8	"	115	22	5.8	"	113	38	3.8
Farthest Bhd		1.8	"	111	18	8.4	"	108	33	5.7
B. Drillship Playbacks--Avoidance Observed										
16 Aug 82	155									
Sonobuoy		2	84	100	16	16	71	95	24	12
Closest Bhd		2	"	100	16	16	"	95	24	12
Farthest Bhd		4.5	"	94	10	21	"	87	16	16
18 Aug 83	164									
Sonobuoy		1.2	78	112	34	7.7	68	111	43	4.5
Closest Bhd		.4	"	118	40	4.2	"	117	49	2.5
Farthest Bhd		1.7	"	110	32	9.0	"	109	41	5.3
C. Dredge Playbacks--Avoidance Observed										
16 Aug 84	161									
Sonobuoy		1	102	118	16	3.3	81	110	29	2.8
Closest Bhd		.15	"	127	25	0.8	"	119	38	.6
Farthest Bhd		2.25	"	113	11	5.5	"	105	24	5.2
24 Aug 84	161									
Sonobuoy		.4	101	125	24	1.2	83	117	34	.8
Closest Bhd		.1	"	131	30	.4	"	123	40	.24
Farthest Bhd		.8	"	122	21	1.9	"	114	31	1.5

*l/s-octave band in which the S:N ratio was highest; centered at 250 Hz for drillship sounds, and at 400 Hz for dredge sounds.

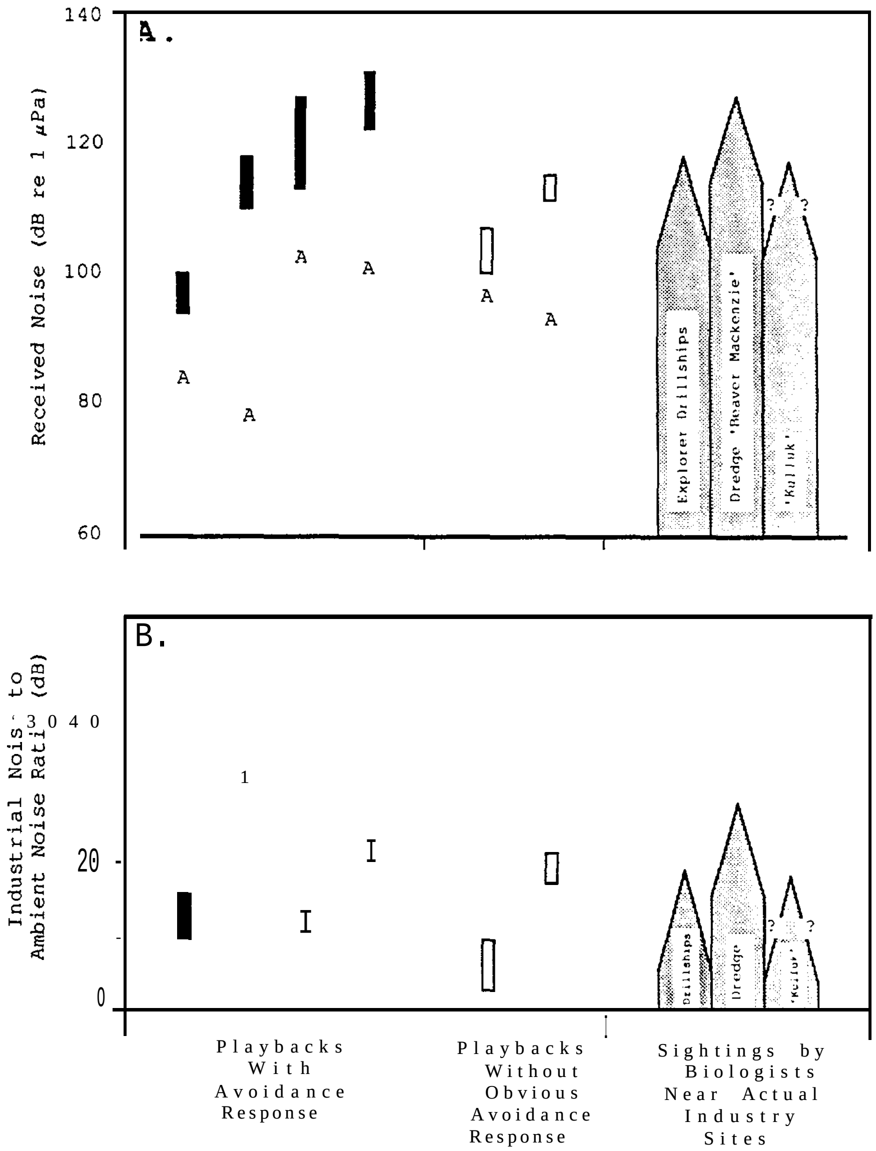


FIG. 10. SCHEMATIC SUMMARY OF BROADBAND (20-1000 HZ) NOISE DATA USED TO DEFINE THRESHOLD OF RESPONSIVENESS CRITERIA FOR BOWHEAD WHALES. A SHOWS ACTUAL RECEIVED AND AMBIENT NOISE LEVELS; B SHOWS INDUSTRIAL NOISE TO AMBIENT NOISE RATIOS. ALL DATA ARE FROM TABLES 4 AND 5. VERTICAL BARS AT LEFT AND CENTER SHOW RANGES OF NOISE LEVELS AT THE LOCATIONS OF ALL BOWHEADS OBSERVED DURING THE SIX PLAYBACK EXPERIMENTS WHEN NOISE LEVELS WERE MEASURED. THE TOP AND BOTTOM OF A BAR REPRESENT THE INDUSTRIAL NOISE LEVELS FOR THE CLOSEST AND MOST DISTANT WHALES UNDER OBSERVATION. EACH "A" SHOWS THE AMBIENT NOISE LEVEL CORRESPONDING WITH THE ABOVE BAR. SHADED BARS AT RIGHT SHOW, FOR THREE ACTUAL INDUSTRIAL SOURCES, THE ESTIMATED INDUSTRIAL NOISE LEVELS NEAR THE CLOSEST WHALES EVER SEEN BY BIOLOGISTS (PEAK OF BAR) AND AT THE DISTANCES WHERE WHALES WERE NUMEROUS (BROAD PART OF BAR).

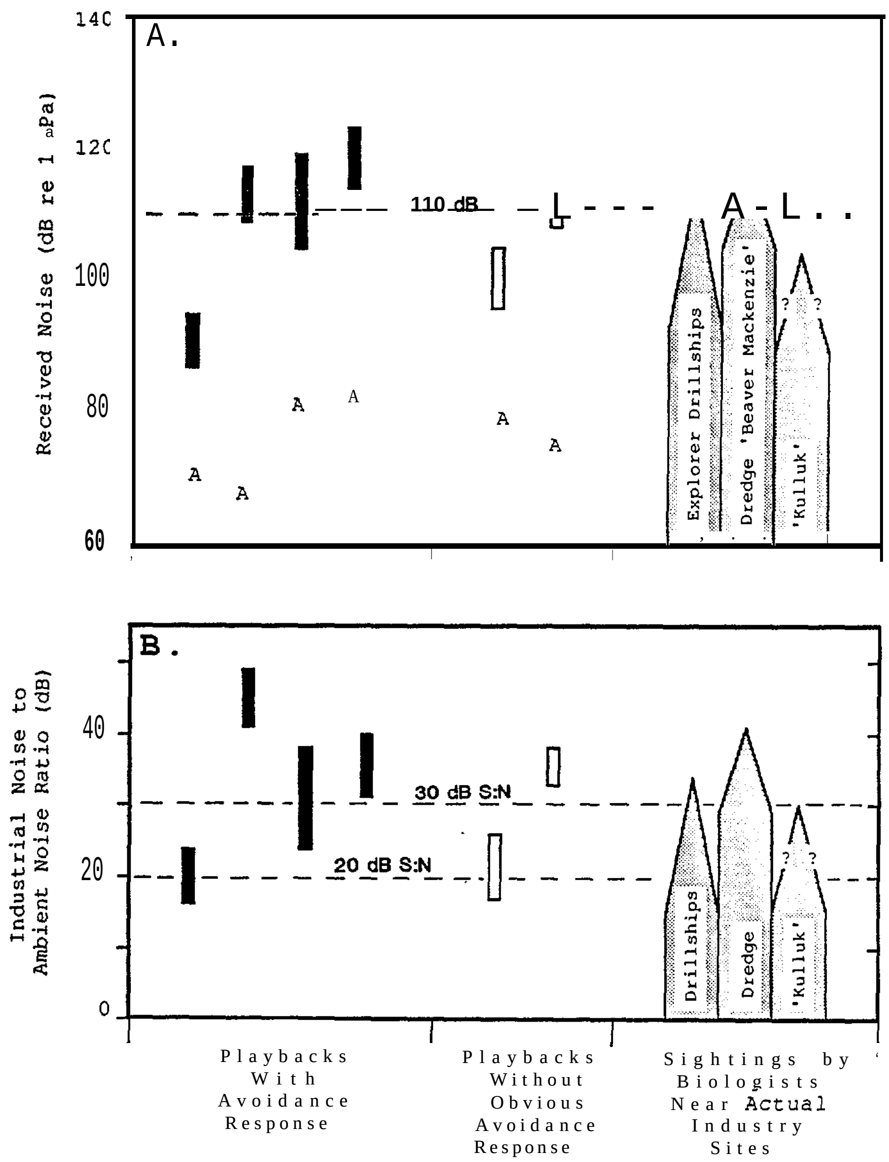


FIG. 11. SCHEMATIC SUMMARY OF 1/3-OCTAVE BAND NOISE DATA USED TO DEFINE THRESHOLD OF RESPONSIVENESS CRITERIA FOR BOWHEAD WHALES . DATA ARE FOR THE 1/3-OCTAVE BAND WITH MAXIMUM SIGNAL-TO-NOISE RATIO; OTHERWISE AS IN FIG. 10.

These results show that there is indeed a "zone of responsiveness" for baleen whales near drillsites and island construction operations. However, if our assumption that whales can hear sounds with signal-to-noise ratios as low as 0 dB is even approximately correct, then the zone of responsiveness is considerably smaller than the zone of audibility. Not surprisingly, given the natural variability of whale behavior, the outer boundary of the zone of responsiveness is indistinct. Some individual whales react to industrial noise at lower received noise levels and signal-to-noise ratios than do others.

Based primarily on the drillship and dredge noise playback data in Table 5, but supplemented by the observations of bowheads near actual industrial sites (Fig. 11; Table 4), <u>we estimate that roughly half of the bowheads react by moving away when the received level of continuous industrial noise is 110 dB in the 1/3-octave band of maximum signal-to-noise ratio, or when the S:N ratio in that band is about 30 dB</u>. These thresholds are based on a subjective evaluation of the data summarized in Figure 11, and are consistent with other corroborative evidence. Figure 11 shows clearly that these assumed thresholds of responsiveness are imprecise. Some individual bowheads react at considerably lower received levels or S:N ratios (e.g., 20 dB S:N), whereas others do not react unless the values considerably exceed 110 dB or 30 dB S:N.

The actual threshold for a given whale at a given time no doubt depends on the activity of the whale (e.g., resting, feeding, socializing, migrating), its situation (e.g., in shallow vs. deep water), and the nature of the sound source. These types of variations in sensitivity of bowheads to noise have been identified and discussed by Richardson et al. (1985b,c). Such variations in sensitivity are presumably responsible for the broad overlap between sound levels that can be tolerated vs. sound levels that can cause avoidance.

A rapidly approaching boat is probably perceived by bowheads as a greater threat than is the continuous noise from a distant stationary site. Hence, reactions to approaching boats would be expected to begin at lower noise levels or S:N ratios. Boats have been identified as the industrial activities that cause the strongest and most consistent responses by bowheads (Richardson et al. 1985b,c). The thresholds of responsiveness estimated from the playback experiments and opportunistic observations of bowheads near stationary sites (summarized in Tables 4-5 and Fig. 10-11) probably do not apply to rapidly approaching boats, although they may apply to the more consistent sounds from distant boats or from boats moving tangentially (see Section 3.5 for further discussion).

In the case of migrating and summering gray whales, more precise data are available concerning probability of avoidance as a function of received noise level (Malme et al. 1983, 1984, 1986a; see Richardson and Malme 1986). Observations for summering gray whales in the Bering Sea and generally consistent with those for migrating gray whales off California in indicating that 0.1 and 0.5 probability of avoidance would occur for received broadband industrial noise levels of 110 and 120 dB re 1 μPa, respectively (Figure 12). These values correspond to industrial : ambient noise ratios of about 20 to 30 dB, respectively, based on the median ambient noise levels expected in the Beaufort Sea in late summer (see Section 3.1).

To translate the above assumptions concerning response thresholds into estimated radii of responsiveness around specific industrial sites, data on source levels of the industrial sounds and on propagation losses at the specific sites of interest are

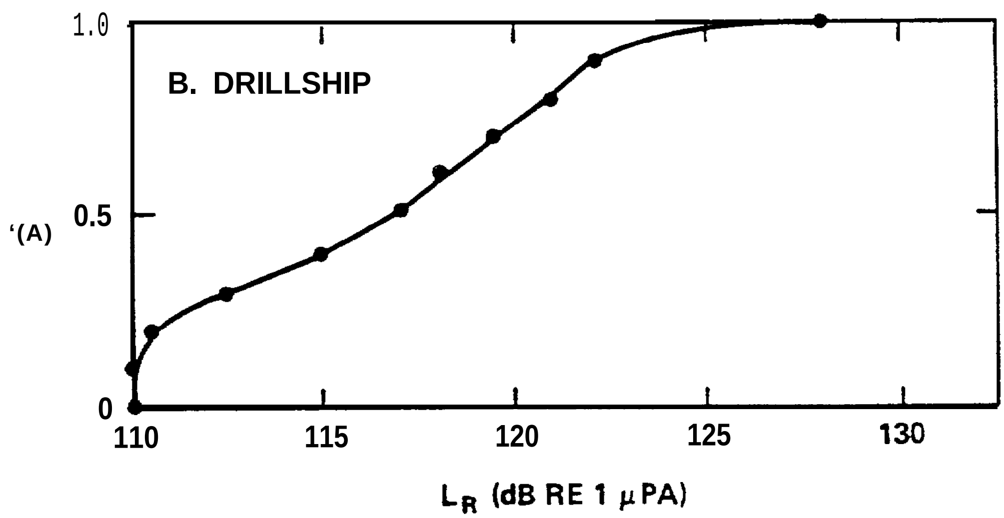


FIG. 12. PROBABILITY OF AVOIDANCE (Pa) OF MIGRATING GRAY WHALES TO SPECIFIC RECEIVED LEVELS (L_R) OF CONTINUOUS DRILLSHIP NOISE. DATA BASED ON OBSERVATIONS OF WHALE RESPONSE TO PLAYBACK SOURCE (MALME ET AL. 1984).* OBSERVATIONS OF RESPONSE OF SUMMERING GRAY WHALES TO THE SAME SOURCE SHOWED SIMILAR AVOIDANCE PROBABILITIES BUT LOW SAMPLE SIZES PREVENTED DETAILED CALCULATIONS (MALME ET AL. 1986a).

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*Playback recording was made by Greene (1985, 1987) 0.2 km from drillship EXPLORER II in 1981. Playback periods consisted of 1-2 min. ramp-up period, a 60-90 min constant level period, and a 1-2 min ramp-down period.

necessary. The present project was designed to provide the necessary data, and to use those data to derive estimates of the zones of responsiveness.

Zone of Masking. -- When there is an increase in the background noise level against which an animal is attempting to detect a sound signal, the signal-to-noise (S:N) ratio is reduced. If, for example, the signal of interest is a whale call, the background noise consists of natural ambient sounds plus any industrial noise that may be present. If the receiving whale is close to an industrial source, the received industrial noise level will probably exceed the natural ambient level, and this will reduce the S:N ratio for the whale call. If the received whale call is intense, it will still be audible despite the reduced S:N ratio. However, if the whale call would be barely detectable in the absence of industrial noise, it may not be detectable in the presence of the noise. Such a call is said to be masked by the industrial noise (Terhune 1981).

The received level of a whale call is likely to be at least roughly related to the distance between the calling and the receiving whales. If the S:N ratio of a whale call received in the absence of industrial noise is low, the call was probably made by a distant whale. Thus, it is primarily the calls from distant whales that will be inaudible if the background noise level increases. Masking by elevated industrial noise levels has the potential to reduce the distance to which a whale can hear calls from other whales, or from other sources of interest.

It is emphasized that the actual importance of masking to whales, particularly baleen whales, is largely unknown. There is little information about the importance of long-distance communication to whales, or about the significance of a temporary interruption in this ability. Long-distance communication must often be interrupted by the natural masking effect of the elevated noise levels associated with storms and moving ice. It is not known whether baleen whales can adapt to increased background noise levels by increasing the intensities or altering the frequencies of their calls; certain toothed whales apparently do this (Au 1980; Au et al. 1985). Source levels of bowhead calls are quite variable (Cummings and Holliday 1985, 1987; Clark et al. 1986)*, so it is possible that bowheads produce more intense calls when background noise levels are high. If the calls or the auditory system of baleen whales have any directional properties, this may provide some resistance to masking. These complications are discussed in more detail by Richardson et al. (1983, 1985c).

Even a slight increase in background noise level has the potential to mask a sound signal that is barely audible. Hence, masking of faint sounds could occur anywhere within the zone where the received level of industrial noise exceeds the natural ambient noise. By this extreme criterion, the zone of masking would be the same as the zone of audibility of the industrial sound. However, many sounds that are relevant to a whale, e.g., sounds from other whales nearby, will have received levels well above natural ambient levels. These sounds would still be detectable, albeit with reduced S:N ratios, even if the background noise level were considerably elevated by industrial noise.

For example, for a bowhead call with source level 180 dB re 1 μPa at 1 m and a bandwidth ≤ 1/3 octave (Clark and Johnson 1984; Cummings and Holliday 1985, 1987), the received level would be about 140 dB at range 100 m and at least 120 dB at 1 km. Near most drillsites and island construction operations in the

*However, some of the apparent variability in source levels may be an artifact of the transmission loss rates assumed in these studies, which appear to be oversimplified.

Canadian Beaufort Sea, received l/3-octave noise levels exceed 140 dB only within about 100 m of the industrial site. Received noise levels exceed 120 dB only within about 0.5 to 5 km (see Richardson and Malme 1986). At distances greater than 0.5 to 5 km from the industrial site, a bowhead could probably hear other bowheads up to at least 1 km away, assuming a detection threshold of about O dB S:N. Thus, short-distance communication would be prevented only for whales close to industrial sites, and the zone where masking is likely to be important will be substantially smaller than the zone of audibility.

To calculate the degree to which masking might reduce communication range for a receiving whale at a given distance from an industrial site, several factors must be estimated. The ambient noise level and the received level of industrial noise at the whale’s location must be determined. In addition, the source levels and propagation characteristics of whale calls (or other sounds of possible interest to whales) must also be estimated. Some information about each of these factors is now available. The “Results” section of this report (Section 3.4.6) contains preliminary estimates of the “zone of masking” for representative industrial activities and one representative site (Corona) in the Alaskan Beaufort Sea.

2.3.2 Methods of estimating zones of influence

A primary objective of this study was to estimate the zone of potential influence of various drilling and dredging sounds that might occur at several specific sites in the Alaskan Beaufort Sea. To do this, it was necessary to determine the source levels and spectral characteristics of those sounds. Propagation losses had to be estimated in order to calculate received levels at various distances from each site.

To estimate the zone of audibility, we assumed that whales can detect sounds whose received levels equal or exceed the ambient noise level. By knowing the range of expected ambient levels at each site, we attempted to estimate the radii at which industrial sounds would attenuate to levels below ambient, and therefore become inaudible (Fig. 13).

To estimate the zone of responsiveness, we had to allow for the fact that most whales apparently react to industrial sounds only if they are considerably stronger than the minimum audible level (see Table 5, Fig. 10, 11). Hence, we also aimed to estimate the radii at which industrial sounds would attenuate to an absolute level of 110 dB (and various other levels), or to 20 dB above ambient, 30 dB above ambient, etc. (Fig. 14).

2.3.2.1 Sources of industrial noise considered

Zone of influence analyses were done for those drilling and island construction operations whose source spectra could be estimated reliably. After review of the industrial sources whose sounds were recorded during this study, six sources were selected for detailed “zone of responsiveness” as well as “zone of audibility” analyses:

1. Tug ARCTIC FOX underway near Erik site in 1985.
2. Pair of tugs forcing a barge against Sandpiper artificial island in 1985.
3. Icebreaker CANMAR KIGORIAK underway at 10 kt (18.5 km/h) near Corona, 10 Sept 1986; KIGORIAK was one of the support ships for the drillship operation at Corona. KIGORIAK was the most powerful ship (16,800 b.h.p.) whose sounds were studied.

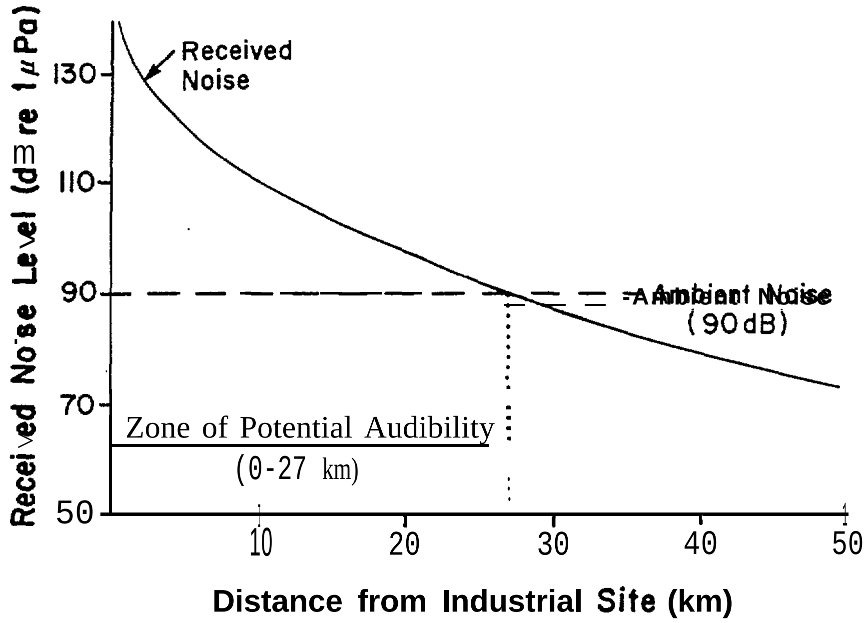


FIG. 13. PROCEDURE FOR ESTIMATING ZONE OF AUDIBILITY FROM INTERSECTION OF RECEIVED LEVEL VS. RANGE CURVE WITH AMBIENT NOISE LEVEL. DATA ARE ARTIFICIAL.

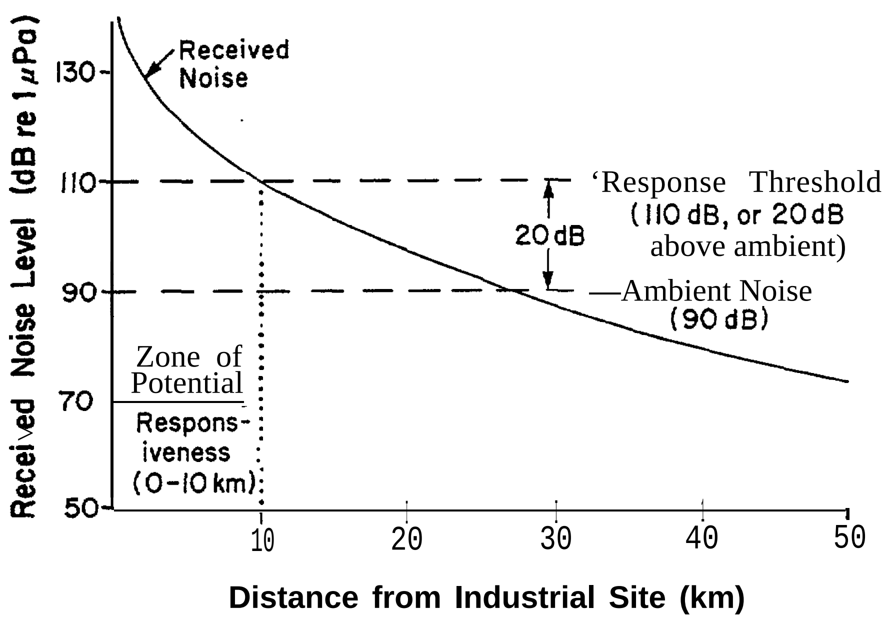


FIG. 14. PROCEDURE FOR ESTIMATING ZONE OF RESPONSIVENESS FROM INTERSECTION OF RECEIVED LEVEL VS. RANGE CURVE WITH RESPONSE THRESHOLD. THE RESPONSE THRESHOLD COULD BE EITHER AN ABSOLUTE NOISE LEVEL (110 dB IN THIS CASE), OR A "SIGNAL : AMBIENT" RATIO (20 dB IN THIS CASE). DATA ARE ARTIFICIAL.

4. Icebreaker ROBERT LEMEUR (9600 b.h.p.) underway at 10 kt (18.5 km/h) near Erik, 18 Aug 1986. LEMEUR was another of the support ships for drilling at Corona.

5. Drilling by EXPLORER II drillship at Corona drillsite in 1986.

6. Drilling at Sandpiper artificial island in 1985 (recorded by Greeneridge Sciences Inc.--Johnson et al. 1986).

Each of these six industrial activities produced more-or-less continuous noise.

The circumstances when these six sets of recordings were made are described in section 3.2. For each of these six types of industrial activity, BBN estimated source levels (i.e., theoretical levels at 1 m range) for various l/3-octave bands, including the bands where levels were highest (see Section 3.2).

For each of these six industrial sources, detailed analyses were done on data from various l/3-octave bands within the 40-4000 Hz range. The selected bands were those for which the source level was high relative to either (a) typical ambient levels in the corresponding band, or (b) source levels in adjacent bands. In most cases, the selected bands met both criteria. The rationale was that sound components whose source levels were high would be the ones that would be detectable at longest ranges. For most sources we considered two to five 1/3-octave bands, not just the one band with maximum signal-to-noise ratio. We did this because propagation losses depend on frequency. The band with highest source level (or highest signal-to-noise ratio at the source) was sometimes one where propagation losses were high. In these cases, another band with slightly lower source level (or source S:N) resulted in higher received levels (or received S:N) because of a lower rate of propagation loss.

Three additional sources of intermittent (variable) sounds are examined in less detail. It is not certain whether the "threshold of responsiveness" criteria derived above are applicable to sounds whose levels or characteristics vary rapidly over time. The three intermittent sources that we considered were as follows:

1. Dredge bucket being hauled up, as recorded at Erik site in 1985. This operation produced stronger sounds than other phases of the dredging cycle at Erik.
2. Tug ARCTIC FOX towing a loaded barge away from Erik site in 1985. This was for a 5 minute run to the dump site. The strongest sounds emitted during any phase of the Erik tugboat/barge operation were recorded at this time, which was short-term with respect to other activities at the site.
3. Icebreaker ROBERT LEMEUR pushing ice near Corona, 4 Sept 1986. This operation produced the strongest sounds (other than seismic pulses) recorded during this study.

Section 3.2 includes information about the peak source levels and spectral characteristics of the sounds from these three intermittent sources, and Section 3.4.2 estimates the zone of audibility around each of them at times of peak sound output. Section 3.6 provides a brief discussion of the possible size of the zone of responsiveness around each of these intermittent sources.

2.3.2.2 Zone of audibility

The six sites studied in 1985, 1986 or both were considered in the zone of audibility analyses; they are Orion, Sandpiper, Hammerhead, Corona, Erik and Belcher. Their locations and descriptions were provided in Figure 1 and Table 1.

For each of these six sites, received levels at various distances were estimated assuming that, in turn, each of the industry sources listed in the previous subsection were present. This was done by applying the site-specific propagation models (section 3.3) to the source level estimates for the various industrial sources (section 3.2). The site-specific propagation models are of the general form developed by Weston (1976), and take account of frequency, water depth, bottom slope, bottom reflection losses, and absorption. For each industrial source, LGL used BBN's propagation models and source level estimates to calculate received level as a function of distance, considering each of the l/3-octave bands that had relatively high source levels.

The assumption that each type of industrial operation listed above might occur at each of the six sites is not realistic. An artificial island of the type at Sandpiper would not be built in water as deep as that at most of the other sites. Conversely, drillships like EXPLORER II have not drilled in water as shallow as that at Sandpiper or Orion. Thus, some of the combinations of industrial sources and sites considered in this analysis are of only theoretical relevance.

For each analysis band, the range of potential audibility was considered to be the range where the received level equaled the expected ambient noise level (Fig. 13). Three different estimates of ambient noise were considered: the 5th, 50th and 95th percentiles. These represent situations when ambient noise is low, average, and high. Section 3.1 describes how BBN estimated these three percentiles for two groups of sites: (1) the shallow westernmost sites, Orion and Sandpiper; and (2) the deeper more easterly sites, Hammerhead, Corona, Erik and Belcher. Insufficient data on ambient noise were collected during this study to develop separate ambient noise statistics for each individual site, e.g., for Orion as distinct from Sandpiper.

For a given site, industrial source, and ambient noise condition, we obtained estimates of the radius of audibility of sounds in each of the l/3-octave bands with relatively high source levels (Appendix D). The zone of audibility was considered to be the maximum of these values. The radius at which the received level equaled the assumed ambient level can be determined from graphs of received level vs. range (Fig. 15). However, the values tabulated in the Results section and Appendix D were actually determined mathematically and printed out by the computer program used to perform the model calculations (see sample printout in Fig. 15).

Because the sites of interest are on a continental shelf where the water depth increases gradually from south to north, radii of audibility were expected to depend on bearing from the site. Orion and Sandpiper Island are south of the main autumn migration corridor of bowhead whales (Davis et al. 1985; Johnson et al. 1986; Ljungblad et al. 1986b, 1987), Consequently, for these sites, we made two estimates of the zone of audibility. One analysis assumed a constant water depth with increasing range (representing propagation parallel to the depth contours, i.e., east-southeast and west-northwest). The other analysis simulated propagation to the north-northeast, and assumed that water depth increased with increasing range at a rate appropriate to the site

WESTON SHALLOW-WAT. SOUND PROP'N MODEL Run date=870602
LGL version for Apple II, including absorption term; Vers. 1.5, 25 May 87

Site = CORONA Source type = LEMEUR.ICEBR

SOURCE LEV (DB) 183 LOCAL ANOMALY (DB) 2
FREQUENCY (HZ) 100 WAT.DEP @ SOURCE (M) 35
BOTTOM SLOPE (-1 TO 1) 0 SINE (CRIT.ANG.), O-1 .2
BOTTOM REFL. 'B', O-5 .3 SOUND SPEED (M/S) 1435

Max R for sph.spr. = .07 km Max R for cyl.spr. = 4.5 km
Max R for multimode= 5.5 km
Max believable R = 51.5 km Max R with Data = 30 km

Ranges where RL = various standard levels:

RL= 75 R= -9	RL= 80 R= 49.3	RL= 85 R= 43.6	RL= 90 R= 38
RL= 95 R= 32.5	RL= 100 R= 27.1	RL= 105 R= 22	RL= 110 R= 17
RL= 115 R= 12.4	RL= 120 R= 8.3	RL= 125 R= 5.4	RL= 130 R= 3.6
RL= 135 R= 1.1	RL= 140 R= .365	RL= 145 R= .119	RL= 150 R= .057

Ranges where RL = 5%, 50%, 95%ile of ambient:
5% (68 dB): R= -9 50% (88 dB): R= 40.2 95% (98 dB): R= 29.3

Ranges where RL = median ambient +5 dB, +10 dB, etc.:

Med+5 : R= 34.7	Med+10: R= 29.3	Med+15: R= 24	Med+20: R= 19
Med+25: R= 14.2	Med+30: R= 9.9	Med+35: R= 6.1	Med+40: R= 4.6

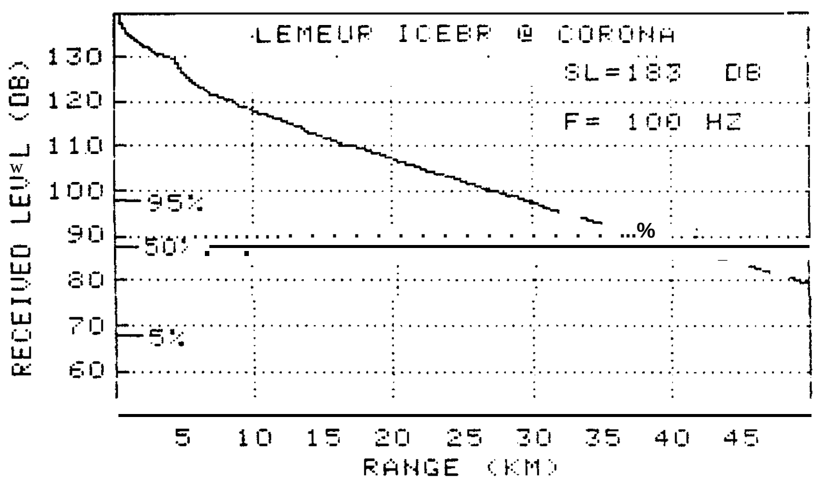


FIG. 15. SAMPLE RESULTS FROM WESTON/SMITH SHALLOW-WATER SOUND PROPAGATION MODEL APPLIED FOR PURPOSES OF ESTIMATING ZONES OF NOISE INFLUENCE AROUND A SPECIFIC INDUSTRIAL SITE. R = Range in kilometers; RL = Received level in dB re 1 µPa; SL = Source Level in dB re 1 µPa at 1m range; F = Frequency in Hz. "-9" means "not calculable--beyond range of model."

in question. The other four sites are within the autumn migration corridor of bowheads (Appendix A), and whales could travel westward either south or north of these sites. Hence, three estimates of the zone of audibility were made for those sites, assuming decreasing, constant, and increasing water depth with increasing range.

In the absence of information about the relative auditory sensitivities of bowhead and gray whales, both species were assumed to be able to detect industrial noise only when its received level equaled or exceeded the ambient level in the corresponding l/3-octave band. Thus, the estimated zones of audibility were the same for both species.

2.3.2.3 Zone of responsiveness*

In this analysis, the "zone of responsiveness" is considered to be the area around an industrial site within which a significant fraction of the whales are expected to exhibit overt avoidance responses, to noise from that site. Based on field studies, responsiveness variables for bowhead whales included avoidance, changes in swimming heading, dive time, etc., while gray whale responsiveness experiments concentrated on measurement of avoidance. The industrial noise level at which whales exhibit a specific behavioral response, such as avoidance, can be specified as a level above the natural ambient (S:N ratio) or as an absolute received level (RL). The literature on animal responses to man-made noise is very sparse, and does not provide guidance on which of these two measures best represents observed reactions. Fortunately, the literature on human responses to industrial noise is much more extensive. Studies of human

*By W.J. Richardson, LGL Ltd., and C.I. Malme, BBN Laboratories Incorporated.

annoyance caused by sources such as traffic noise and aircraft flyover noise, as discussed by Kryter (1985), may be helpful in identifying the most appropriate threshold criteria for the avoidance reaction in whales.

In general, annoyance reactions in humans correlate better with the absolute level of the intruding noise than with the maximum S:N ratio (Robinson et al. 1963). However, when the background noise level is not much less than the received level of the intruding noise, the threshold of annoyance is shifted upward (Spieth 1956; Pearsons 1966) and the S:N ratio is the more relevant parameter. As a result, the usual practice in determining annoyance criteria for specific types of noise involves using psychoacoustic testing procedures to measure the sound levels that produce a quantifiable level of annoyance. Correction factors based on the prevailing background noise levels in specific locations may then be applied (Kryter 1985).

The “zone of responsiveness” criteria considered in this report include both the S:N ratio approach and the absolute received level approach. The available data for bowhead whales do not allow us to determine whether behavioral responses are better correlated with one or the other of the two possible measures of acoustic exposure. (The available database is too small and the observed values of S:N and RL are too closely correlated to allow a clear distinction between criteria.) The present report estimates the zone of noise influence based on both the S:N and absolute RL criteria for both bowhead and gray whales.

Data from recent studies of the behavioral reactions of bowhead and gray whales to industrial noise were summarized by Richardson and Malme (1986) and, briefly, in Tables 4 and 5 and Figures 10 and 11, above. These data were used to estimate the industrial noise levels and industrial : ambient noise ratios at which the two species do and do not react. There is no one threshold value of RL or S:N above which all whales react and below which none react. That is, there is a gradation of responsiveness for a given received level or signal-to-noise ratio. Instead, above some minimum industrial noise level, the probability of reaction increases with increasing noise level, at least in the case of migrating gray whales (Figure 12; Malme et al. 1983, 1984).

In the case of bowheads, few if any individuals appear to react overtly to near-continuous industrial noise levels less than 15 dB above the natural ambient level. Some individuals apparently tolerate much higher levels (see Tables 4, 5). However, a minority of the bowheads move away in response to the gradual onset (over 10-13 rein) of drillship or dredge noise whose peak level is 20 dB or more above ambient. Roughly half of the bowheads move away in response to sounds with signal to noise ratio 30 dB or an absolute received level of 110 dB. A few bowheads apparently tolerate noise levels up to 40 dB above ambient. These levels and industrial:ambient ratios are based on levels in the l/3-octave band with the maximum level of industrial noise relative to average ambient noise in the corresponding band (Fig. 11). As a first approximation, the median zone of responsiveness of bowhead whales to near-continuous industrial noise has been defined as the area where the received noise level is 30 dB or more above ambient. However, some individual bowheads respond at lower S:N ratios (i.e., greater ranges), and others apparently do not respond overtly unless S:N is more than 30 dB (i.e., closer ranges). Table 6 summarizes the assumptions associated with these response threshold criteria for bowheads.

As a first approximation, the zone of responsiveness of gray whales to near-continuous noise sources, similar to that of bowheads, is considered to be the area where the received noise level is 20 dB or more above ambient (see Section 2.3.1 and Table 6).

The radii within which the industrial noise level would exceed the median ambient level by 20 dB, 30 dB and 40 dB (possible criteria for zone of responsiveness) were determined in the same way as the radii where industrial noise equaled ambient noise (zone of audibility, Section 2.3.2.2). We also estimated the radii within which the absolute noise level would exceed 110 dB, which is another possible criterion of responsiveness. Separate calculations were done for each combination of industrial sources, six sites, and 2 or 3 bottom slopes per site, considering the l/3-octave bands that had high source levels (Appendix D).

2.3.2.4 Alternative criteria and alternative industrial sources*

It should be recognized that there is considerable variability in responsiveness of differen= whales, and there may be differences of opinion about the most appropriate criterion for defining the zone of responsiveness. Responsiveness may depend on the type of noise and not just its level; whether the noise is constant, increasing, decreasing or fluctuating in intensity; on the activity of the whales, e.g., migrating, feeding, socializing or resting; and on the location, e.g., shallow vs. deep. Future studies are likely to refine present information about response thresholds. Hence, we have also calculated the ranges where the received levels would diminish to a variety of other S:N ratios

*By W.J. Richardson, LGL Ltd.

Table 6. Assumptions underlying response threshold criteria used for bowhead and gray whales.

NOTE : A basic general assumption used in this study is that whales respond to low frequency sound intensity above a given level.

A. BOWHEAD WHALES

Bowheads Near Actual Oil Industry Sites

1. It is assumed that bowhead whales rarely approach closer to industrial sites than the distances of closest approach observed by biologists during several seasons of work in the Canadian Beaufort Sea (Table 4, from Richardson and Malme 1986).

2. Received sound levels at the times and locations of those close sightings are assumed to be similar to those measured by Greene (1985, 1987) at corresponding distances from the same industrial activities.

3. Ambient noise levels at the times and locations of those close sightings, which were not measurable due to masking by industrial noise, are assumed to be similar to the average ambient levels recorded by Greene (1987).

4. Some bowheads are expected to exhibit avoidance reactions at greater distances, i.e. at lower received noise levels, than those associated with the closest whales.

Playback Experiments

5. Reactions of bowheads to a given level of industrial noise are assumed to be similar for whales exposed to (a) continuous noise from actual industrial operations vs. (b) the same received level of noise during LGL's short-term playbacks of drillship and dredge noise.

Other Assumptions

6. It is assumed, based on strong evidence (Richardson et al. 1985b,c; Richardson and Malme 1986), that bowhead whales do not necessarily react to any industrial sound that they can hear; the received level of the industrial sound must exceed some threshold of responsiveness before bowheads will react.

7. Thresholds of responsiveness are known to vary from time to time and whale to whale, probably depending on factors such as whale activity, water depth, nature of sound source, and variability in sound. The best that can be achieved with present evidence is to define noise thresholds at which roughly half of the bowheads would be expected to exhibit avoidance responses. The thresholds are statistical phenomena; in any single incident, all individual bowheads may react to the threshold sound level, or none may do so.

Table 6. (Cent). Assumptions underlying response thresold criteria used for bowhead whales.

8. Reactions to a given received level of <u>continuous</u> industrial noise are, to a first approximation, assumed to be similar regardless of the type of noise source. (This phenomenon has been demonstrated in gray whales by Malme et al. 1983, 1984.) Thus, criteria of responsiveness based on observations of bowhead reactions to noise from one drillship or dredge are assumed to be applicable to other sources of continuous noise.

9. As a specific case of assumption (8), bowhead sensitivity to more-or-less steady received noise levels from distant ships is assumed to be similar to sensitivity to drillship and dredge noise, However, sensitivity to increasing noise levels from approaching ships <u>is not</u> assumed to be the same as that to steady noise levels.

10. Present evidence is inadequate to show whether the thresholds of responsiveness derived for more-or-less continuous noise sources are applicable to "intermittent" sources whose source levels vary over time,

11. Present evidence is inadequate to show whether the most appropriate criterion of responsiveness is an absolute noise level or a signal-to-noise ratio (i.e. industrial noise to background ambient noise ratio). Consequently, both approaches are examined in this study.

B. GRAY WHALES

1. Assumptions 5 through 11 given above for bowhead whales are also relevant for gray whales.

2. No data are available from observations of gray whale response to industrial noise in the Beaufort Sea. It is necessary to assume that exposure level response criteria obtained from studies made elsewhere (Malme et al. 1983, 1984,, 1986a) are applicable in the acoustic environment of the Alaskan Beaufort coast.

besides 20, 30 and 40 dB (e.g., Fig. 15). Furthermore, we determined the ranges where the received level would equal various absolute levels, e.g., 100, 110, 120, and 130 dB re 1 µPa (Fig. 15). All of these figures are tabulated in Appendix D but some are not considered in the Results.

The six industrial activities considered in detail in the "zone of responsiveness" section of this report (Section 3.4.3) do not include all possible industrial activities that could occur near drillsites in the Alaskan Beaufort Sea. Appendix E was prepared by LGL to allow readers to look up the expected zone of influence for other sources of continuous industrial noise. To look up the expected zone of influence of such an industrial activity, it is necessary to know the source level of its sounds in the dominant 1/3-octave band. Appendix E contains tables for each of the six sites considered in this report. For various combinations of frequency and source level, the expected zone of audibility under median ambient noise conditions was calculated and tabulated, as was the expected zone of response based on each of the S:N and RL criteria considered in the report. BBN's Weston/Smith propagation models for each site were used by LGL in order to derive these tables. Appendix E contains lookup tables for the "zero bottom slope" case, i.e., for east-west propagation along the isobaths. Similar tables for southward and northward propagation are available from LGL Ltd. on request.

As noted earlier, the threshold of responsiveness criteria developed above refer primarily to near-continuous industrial noise. It is not known whether the same criteria are applicable to <u>transient</u> sources such as an approaching boat, or to intermittent sources such as an icebreaker alternately pushing ice and then backing away. Therefore, our detailed zone of responsiveness estimates (Section 3.4.3) are restricted to sources of near-continuous noise. For transient sources such as an approaching boat, there is evidence that reactions may be more pronounced, and that the thresholds of responsiveness may be lower than for continuous sources (see Section 3.5). For intermittent sources, even if the criteria are generally applicable, it is not known whether the criteria should be applied to the maximum sound levels that are emitted at certain stages of the industrial operation, or to some type of average sound level; these questions are discussed in Section 3.6.

2.3.2.5 Zone of masking

The effect of industrial noise on communication range was estimated for whales near one site, Corona. The same methods would be applicable at other sites, but to simplify the presentation we have considered only east/west sound propagation near Corona.

The frequency and source level of whale calls affect the distance to which they can be detected. We considered whale calls near three frequencies: 100 Hz, 200 Hz and 600 Hz. Most bowhead calls are near 100-200 Hz, although "high" calls are typically near 600 Hz (Clark and Johnson 1984; Würsig et al. 1985). Source levels of bowhead calls have been reported to range from about 129 dB to 189 dB (Cummings and Holliday 1985, 1987) or from about 128 dB to 178 dB (Clark et al. 1986). We considered calls with levels 140, 150, ... 190 dB.

The Weston/Smith sound propagation models derived for the Corona site were used to predict received levels of bowhead calls and of industrial noise in relation to source level, frequency and distance. The expected ambient noise level was taken into account, considering the 1/3-octave band centered at the frequency of the bowhead call. The results were used to evaluate the effect of distance from an industrial source on the radius of detectability of a bowhead call.

We assumed that a bowhead call will be detectable if its received level equals or exceeds both the ambient noise level and the received level of industrial noise. A whale call is assumed to be undetectable if its received level is less than either the ambient noise level or the received level of industrial noise. Ambient and industrial noise levels are based on the 1/3-octave band centered at the frequency of the whale call, on the assumption that the critical bandwidth for whale hearing is 1/3 octave (see Section 2.3.1).

3. RESULTS

The underwater acoustic environment of the Alaskan Beaufort Sea defined in terms of ambient noise statistics, industrial noise characteristics associated with six drillsites and sound propagation loss characteristics of the region is presented in Sections 3.1 through 3.3, respectively, based on field measurements made during the summers of 1985 and 1986. These data have been used, together with the results of prior research by LGL Ltd. and BBN regarding bowhead and gray whale response to acoustic stimuli, in estimating potential zones of influence of industrial noise for those species. Those estimates, for continuous noise sources, are provided in Section 3-4. A special example of continuous noise, that from a directly approaching vessel is discussed in Section 3.5, and intermittent source implications are discussed in Section 3.6.

3.1 Ambient Noise Statistics

Ambient noise levels are influenced by natural environmental factors including wind, rain, snow, surf, and wave action and, in Arctic regions, ice. The strong influence of wind and wave action on ambient noise levels was the basis for an important report by Knudsen et al. (1944), presenting a family of curves of ambient noise levels as a function of frequency for a series of wind and sea-state conditions in deep water. The "Knudsen curves" have become a standard reference for underwater acoustics research. The presence of pack ice will reduce wave action resulting in an ambient noise level which is lower for a given wind condition than would be encountered in open water for the same winds. However, when ice approaches 10/10 cover, impulsive noises associated with such factors as cracking and ice-block impact add to the underwater background noise.* Ideally, and particularly in the context of this project, the terms ambient noise and natural background noise are synonymous although it is often not possible to obtain a pure natural background measurement because of distant shipping, in particular. Distant shipping has been shown (Wenz 1962; Urick 1983) to be a major contributor to ambient noise, particularly at low frequencies (below 100 Hz). Biological noise from fish, crustacea, and marine mammals is part of the natural background and can be transient, short-term or continuous (e.g., snapping shrimp) in nature.

Ambient noise is commonly presented in two categories; relating sound levels to shallow water and deep water conditions as in Wenz (1962) and Urick (1983). The term shallow water is often applied to continental shelf and coastal regions, and deep water usually applies to open sea or areas of the ocean which are not restricted by land masses and are off the continental shelf. In the strict use of these terms, the Alaskan Beaufort sites visited under this project are all shallow water. However, since two sites are located in less than 18 meters of water and four are in 28 to 50 meters of water, we have developed "shallow site" and "deep site" ambient noise statistics for this report.

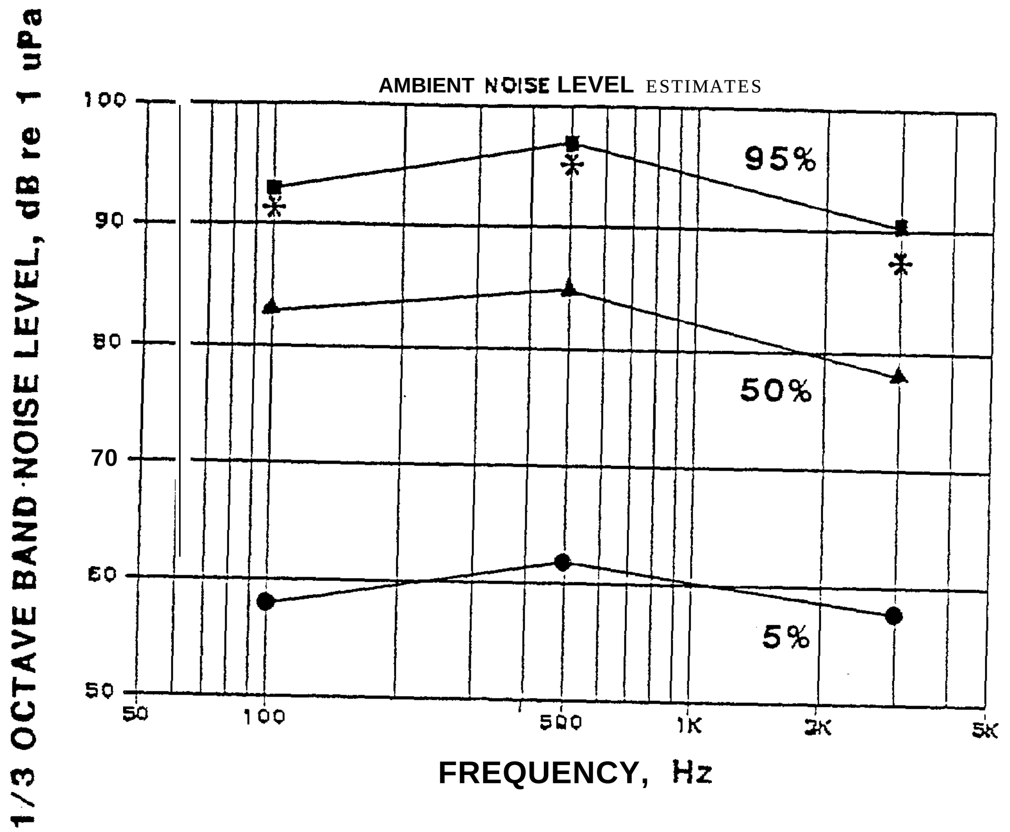
Short-term (10 to 15 minute) measurements of ambient noise were made at all of the sites at various times of the day before and after performance of other acoustic measurement tasks associated with acoustic transmission loss or industrial noise measurements. At some sites, particularly those to the east of Prudhoe Bay, it was" common to encounter seismic survey acoustic impulses in the background, negating the ability to obtain clean

*Glacial ice (not a factor in the Alaskan Beaufort) generates very high level "frying" sounds as miriads of compressed air bubbles in the ice are released in the ice melting process.

ambient data. Nevertheless, sufficient data were acquired to provide the basis for deriving a statistical description of the ambient noise conditions along the Alaskan Beaufort continental shelf. The short-term ambient results were supplemented with historical Arctic ambient noise data (Urick 1983; Moore et al. n.d. [1984]) and through application of known relationships between wind and ice conditions and underwater noise (Knudsen et al. 1944; Wenz 1962). Wind and ice statistics for the Alaskan Beaufort region for the bowhead migration periods were obtained from the NOAA Climatic Atlas (Brewer et al. 1977) and from the Alaska Marine Ice Atlas (LaBelle et al. 1983).

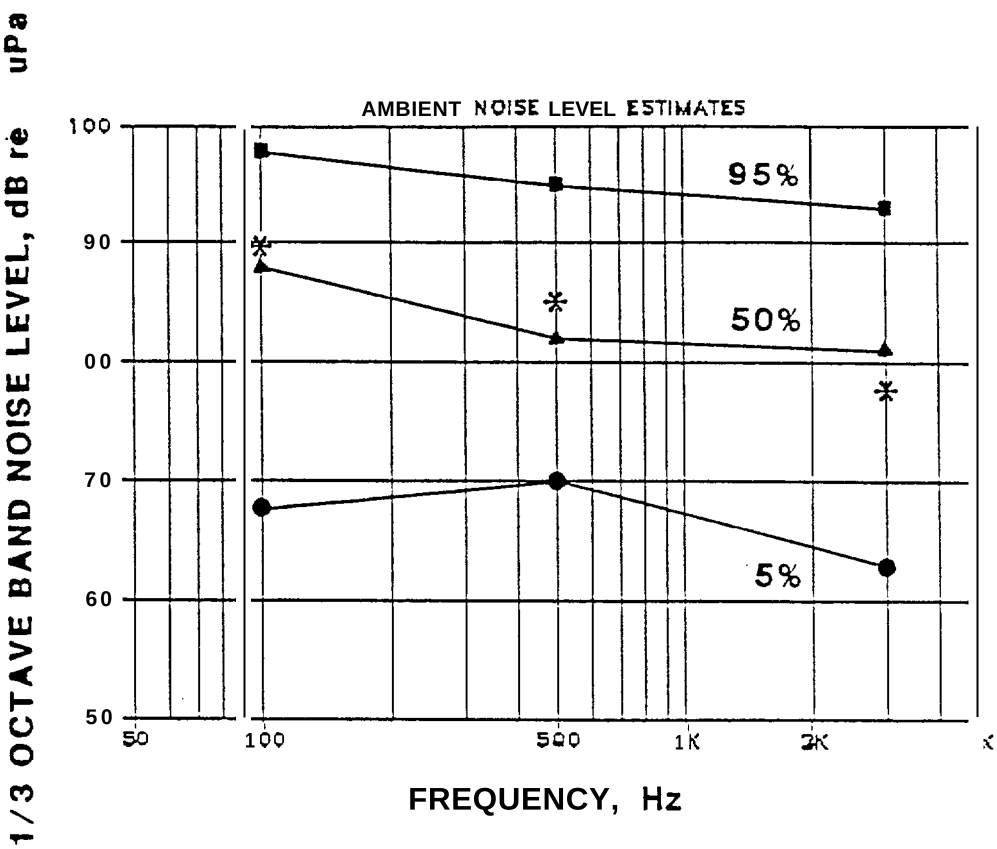
During the 1985 field season, ambient noise data which were not influenced by industrial noise or seismic survey impulses were acquired at Orion, Sandpiper, and Corona. As discussed in Section 2.2.2.1, cumulative distribution functions were derived for those ambients providing three curves which indicate when the background noise level is equal to or less than the level shown 95% of the time, the median or 50th percentile noise level and the level below which the noise occurs 5% of the time. The results of that analysis are given as spectrum levels (1 Hz bandwidth) in Appendix B for Orion and Sandpiper (the shallow sites) and for Corona which was used to represent the deep sites (Corona, Hammerhead, Erik, and Belcher). Those curves were used as the basis for deriving one-third octave band ambient noise 95th, 50th, and 5th percentile curves, which were adjusted considering historical data concerning wind and ice conditions in the Alaskan Beaufort.

Figures 16 through 20 provide those curves of ambient noise statistics to be expected at all six sites together with, respectively, the mean short-term ambient noise levels measured at Sandpiper, Hammerhead, Corona, Erik, and Belcher in 1986. In most cases, the short-term ambient levels fell within the 5th and



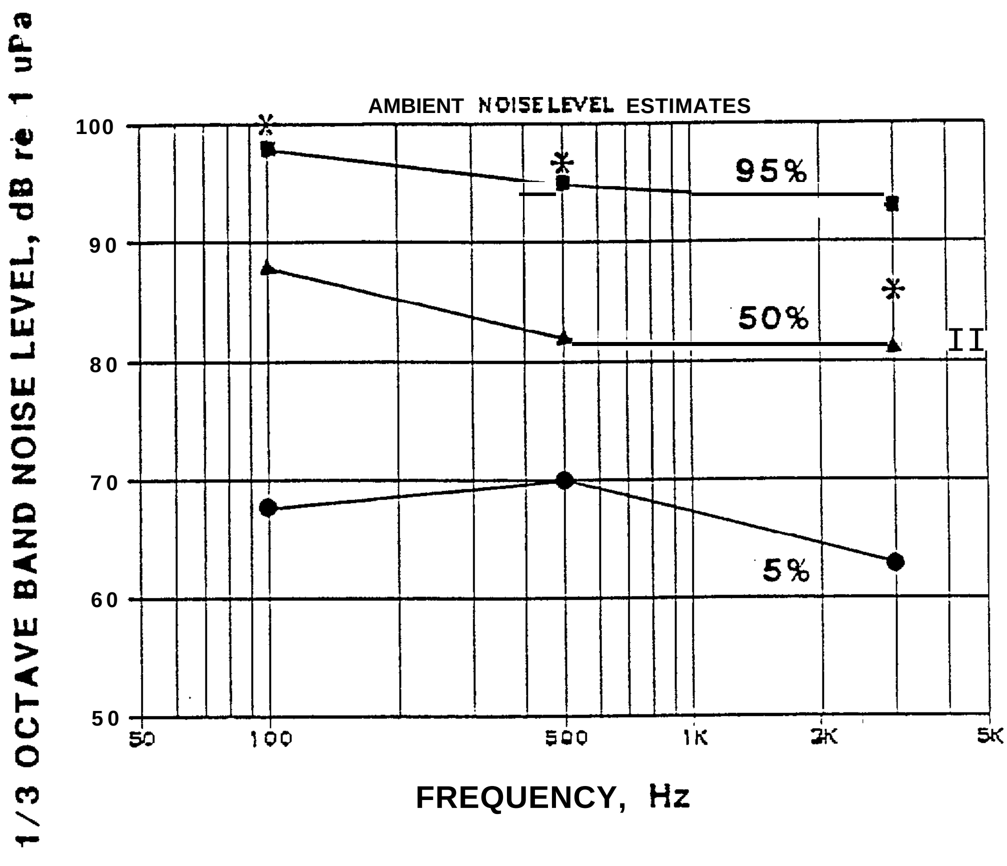
* = Sandpiper mean short-term level in 1986, in 8-16 knot winds, no ice, two noise samples

FIGURE 16. ESTIMATED AMBIENT NOISE LEVEL PERCENTILES FOR THE FALL MIGRATION PERIOD AT THE SANDPIPER AND ORION SHALLOW SITES. VALUES ARE EXPRESSED ON A 1/3 OCTAVE BAND (OB) BASIS .



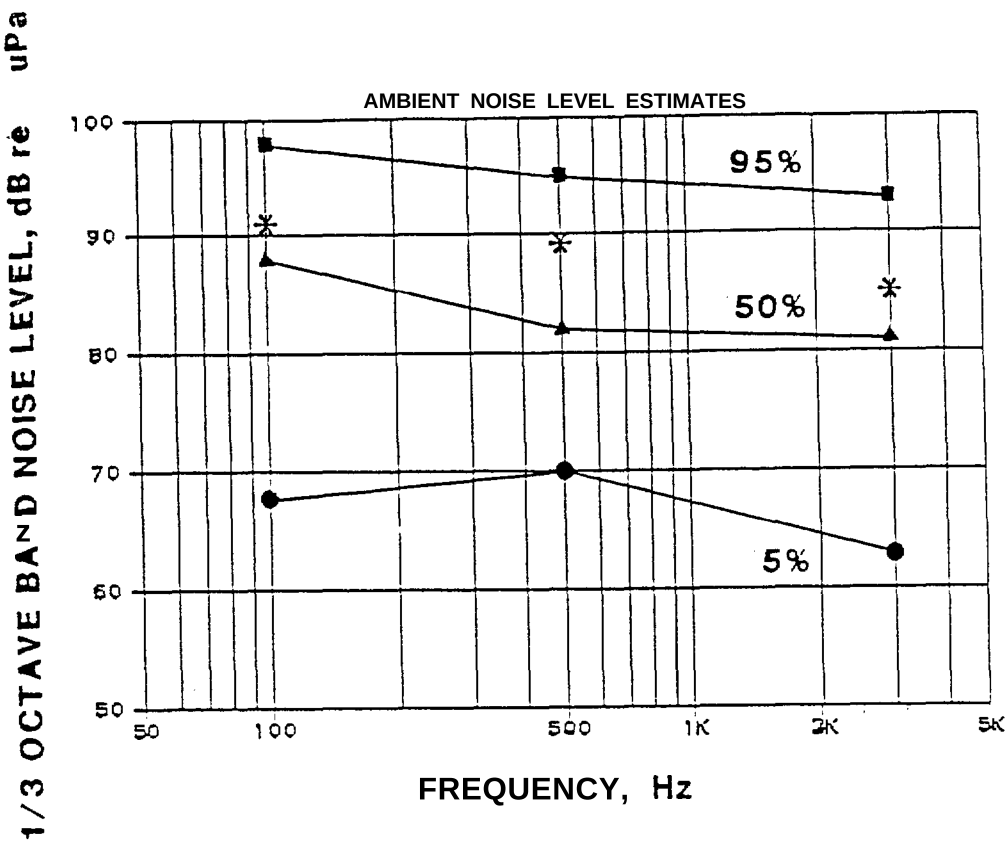
* = Hammerhead mean short-term level in 1986,
5 knot winds and 1/10 ice, one noise sample

FIGURE 17. ESTIMATED AMBIENT NOISE LEVEL PERCENTILES FOR THE FALL MIGRATION PERIOD AT THE HAMMERHEAD, CORONA, BELCHER, AND ERIK DEEP SITES. VALUES ARE EXPRESSED ON A 1/3 OCTAVE BAND (OB) BASIS.



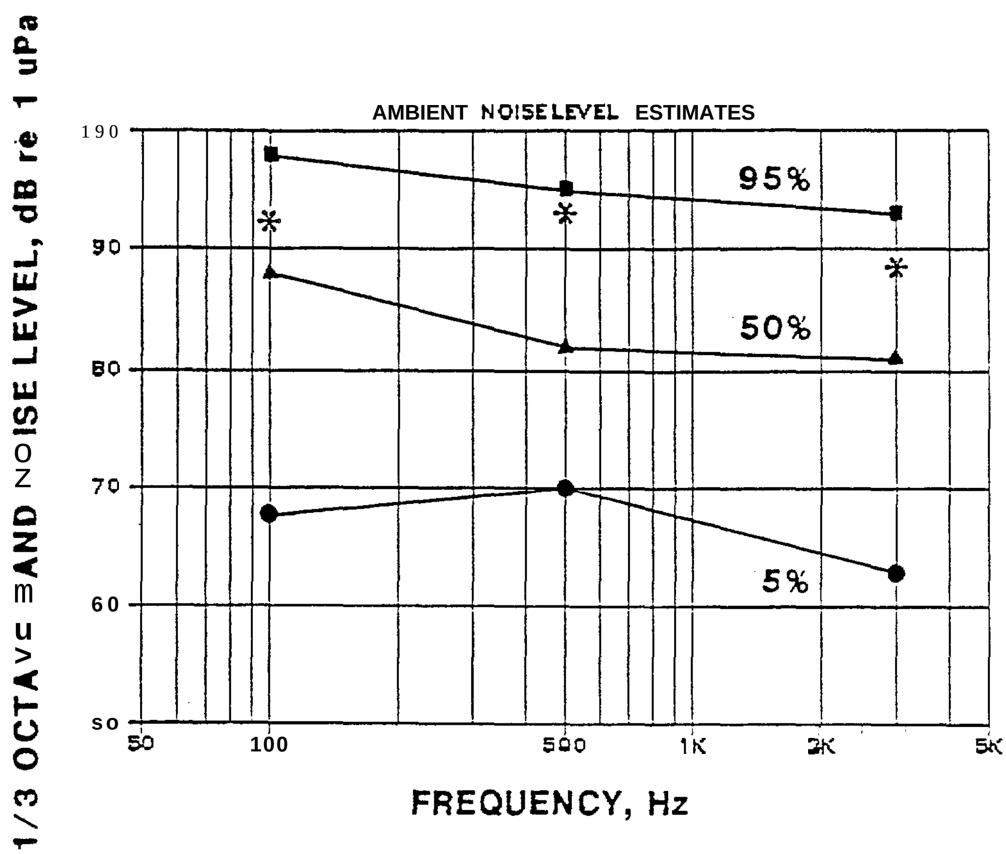
* = Corona mean short-term level in 1986 during very frequent industrial noise and seismic survey activity, 5 to 13 knot winds, large broken ice 2 miles away, three noise samples

FIGURE 18. ESTIMATED AMBIENT NOISE LEVEL PERCENTILES FOR THE FALL MIGRATION PERIOD AT THE HAMMERHEAD, CORONA, BELCHER, AND ERIK DEEP SITES. VALUES ARE EXPRESSED ON A 1/3 OCTAVE BAND (OB) BASIS.



* = Erik mean short-term level in 1986,
2-12 knot winds, 1/10-2/10 ice, six noise samples

FIGURE 19. ESTIMATED AMBIENT NOISE LEVEL PERCENTILES FOR THE FALL MIGRATION PERIOD AT THE HAMMERHEAD, CORONA, BELCHER, AND ERIK DEEP SITES. VALUES ARE EXPRESSED ON A 1/3 OCTAVE BAND (OB) BASIS.



* = **Belcher** mean short-term levels in 1986,
5-20 knot winds, no ice, four noise samples

FIGURE 20. ESTIMATED AMBIENT NOISE LEVEL PERCENTILES FOR THE FALL MIGRATION PERIOD AT THE HAMMERHEAD, CORONA, BELCHER, AND ERIK DEEP SITES. VALUES ARE EXPRESSED ON A 1/3 OCTAVE BAND (OB) BASIS.

95th percentile limits as shown in those figures and reported in the interim report (Miles et al. 1986). The 1986 measurements at Corona were the one exception. However, in that case it was not possible to obtain measurements without influence from the nearly continuous industrial noise activities proceeding at Corona. While it may be useful to present the 1986 data from Corona in Fig. 18 to demonstrate the impact of industrial noise on natural ambients, those data should not be taken as being representative of natural background noise at that site. Rather, the noise statistics in that figure are considered to be valid as are those in all of the figures. The other 1986 median levels appear to have been influenced by wind and ice conditions and possibly by industrial noise to a limited extent at low frequencies. It is particularly interesting to note that Johnson et al. (1986) report long-term ambient noise statistics measured at Sandpiper over periods of 166-188 hours in September-October 1985 during a variety of ice and wind conditions. Their data are very similar to the solid curves in Fig. 16 except for the 5th percentile level at 100 Hz which tends to be about 10 dB higher than shown. Those higher levels were apparently related to seismic impulse noise and Sandpiper industrial noise.

The ambient noise statistics shown in these figures are representative of long-term background noise conditions in the Alaskan Beaufort Sea in the September to October migration time frame and have been based on measurements made in 1985-86 and adjusted considering wind and ice statistics for the region. These curves have been used in the calculation of zones of influence of industrial noise on migrating and feeding bowhead whales and gray whales presented later in this section.

3.2 Industrial Noise Sources

The radiated noise characteristics of five industrial activities were measured by BBN and Greeneridge Sciences during the 1985 field season. These were dredge operation and tug maneuvers at the Erik site, EXPLORER II drilling operation at the Hammerhead site, drilling activity on Sandpiper Island, and tug operations near the island. During the 1986 field season, recordings were made of a transit of the icebreaker ROBERT LEMEUR at the Erik site, operation of the EXPLORER II drilling at the Corona site (including attendant icebreaking activity by the ROBERT LEMEUR), and a transit by the icebreaker KIGORIAK. Seismic survey sounds were also recorded at several sites. Belcher, Hammerhead, and Sandpiper sites were not occupied by industrial activities during the 1986 field season.

In the following sections we present representative narrow-band and l/3-octave radiated noise spectra with associated source level estimates for the sources measured.

3.2.1 Erik Site - dredge operation, tug maneuvers, and ROBERT LEMEUR transit

Dredge Operation at the Erik Site

BBN visited the Erik site twice in 1985 on September 9th and 13th. The data presented here are from the 13th. On the 9th, the fog was too thick to observe the dredge operation during glory hole construction and coordinate the acoustic measurements with specific dredge activities. The weather on 13 September was clear, sea state O-1, light winds with only an occasional piece of sea ice.

During the 13th, we observed the dredge ARGILOPOTES drop its clam-shell into the water, winch it back up, move the clam-shell along an overhead rail and empty its contents into an attendant barge. Measurements were made at two hydrophore depths, 7 and 12 m, and at distances of 1 to 2 km. The water depth was about 38 m. No acoustic noises attributable to the dredge itself were observed except during the clam-shell retrieval phase. Two sounds were apparent during retrieval. First, a “clank” was heard as the clam-shell jaws closed underwater. This sound was very short, and although audible, had little acoustic energy and therefore is not addressed here. Second, a dominant buzzing sound occurred while the winch hauled the loaded clam-shell back to the surface and was produced by the motor which drove the winch. The radiated noise was rich in harmonics of 125 Hz, and a sample narrowband spectrum is shown in Fig. 21A. Note that a strong fundamental frequency, 125 Hz, was not observed. Examination of this and other data samples indicates that significant acoustic radiation occurred at frequencies below 3.5 kHz.

Throughout these measurements, seismic exploration activity in the vicinity was very prevalent. Examination of the time series from one of the hydrophores on a strip chart recorder indicates that two seismic vessels were in operation. One vessel generated impulses roughly every 9 sec and the other at 14 sec intervals. Due to this interference, third octave band analysis is not appropriate because the measurement intervals between impulses were not of sufficient duration to generate an uncorrupted third octave band spectrum, much less permit any spectral averaging to get a statistically stable sample. If we averaged over an 8 sec period, the seismic noise masked the dredge noise at frequencies below about 400 Hz and significantly affected higher frequencies.

Narrowband analysis on the HP3562 dynamic signal analyzer can produce spectra from shorter data sampling intervals for the same spectral bandwidth. Judicious manual operation allowed us

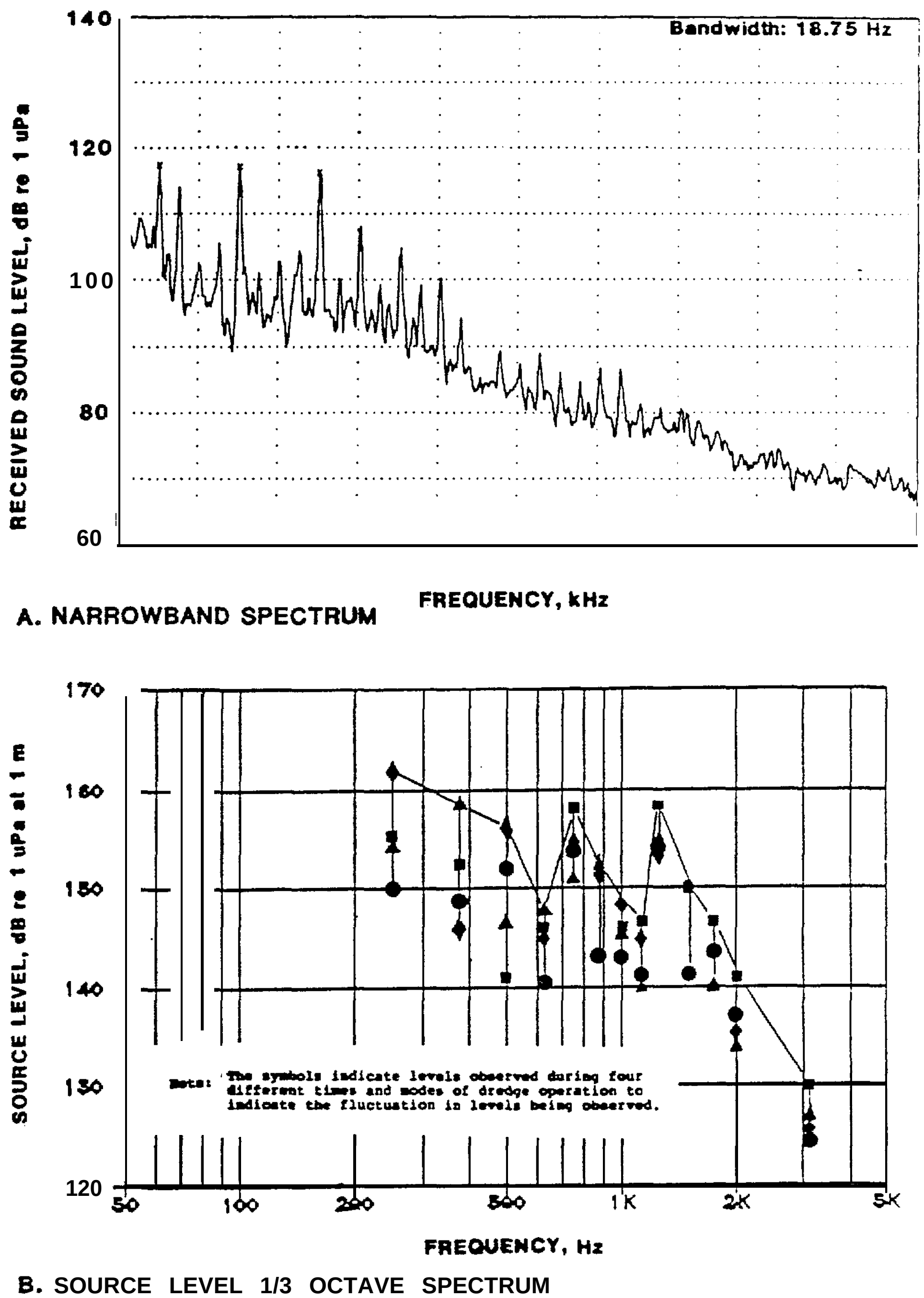


FIG. 21. INTERMITTENT RADIATED NOISE SPECTRA FOR CLAM-SHELL DREDGE ARGILOPOTES, AT ERIK SITE 1985. (FLUCTUATION IN LEVEL DUE TO DIFFERENCES IN CLAM-SHELL RETRIEVAL OPERATIONS.)

to calculate uncontaminated results. Fortunately, the dredge acoustic signature is dominated by reasonably narrowband tonals. If a third octave band encompasses a single strong tonal whose level is ≥ 9 dB above the levels of the rest of the frequencies in that band, the third octave band level is equal to the tonal level, to within 1 dB. Examination of Fig. 18A shows that for the most energetic tonals (250, 750 and 1250 Hz), these narrowband components dominate their respective third octave bands by more than 9 dB and therefore their third octave band levels equal the tonal levels.

Four independent measurements of clam-shell retrieval sounds (taken at four ranges) were corrected for the site specific TL characteristics (Sec. 3.3). The tonal levels were then extracted and are shown in Fig. 21B. Below 1.25 kHz, source level estimates for each harmonic are displayed. At higher frequencies, a few tonals are presented to show the signature envelope. We hypothesize that the variability is due to differences in the weight of clam-shell loads and changes in the acoustic propagation characteristics during the measurements as the water masses changed and the receiver platform drifted.

<u>Tug Operations at the Erik Site</u>

The tug ARCTIC FOX assisted the dredge ARGILOPOTES at the Erik site on 13 September 1985. Its function was to transport a barge roughly 0.5 n.m. from the dredge, dump the material and return the barge to the dredge. The procedure consisted of backing the tug away from the dredge, maneuvering to the opposite side of the dredge, attaching to the barge, and hauling the barge off. The first and last steps produce the highest level radiated noise because the tug propeller is cavitating. No sounds were heard as the barge was emptied. (The environmental conditions were described previously.)

Figure 22A shows a sample narrowband received signature taken while the tug backed away from the barge approximately 0.9 km away. The low frequency components below about 400 Hz are due to local seismic survey activity. In general, the radiated tug noise is broadband with no significant tonals. The propeller blade rate harmonics were masked by the seismic signals.

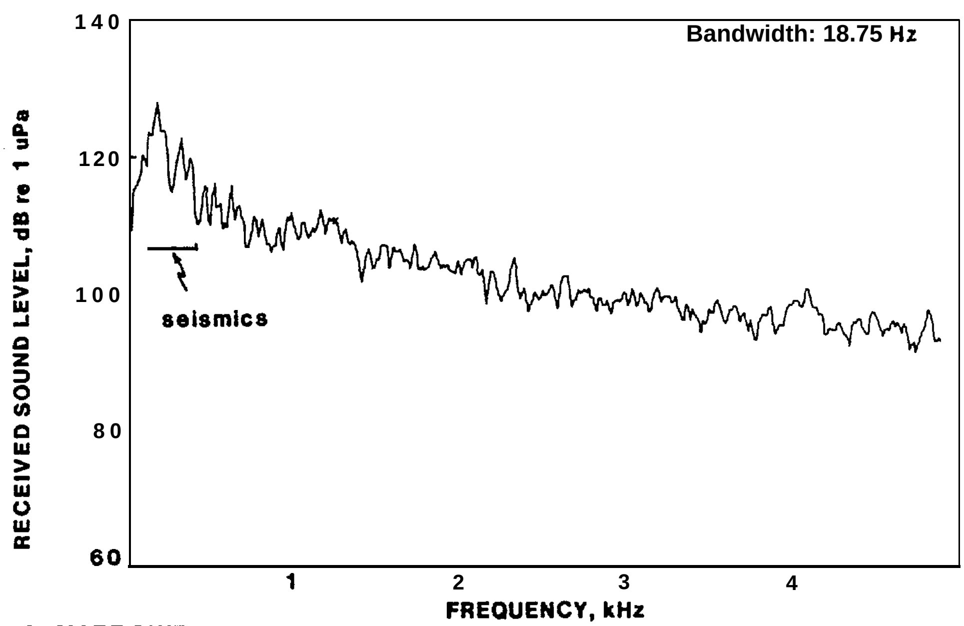
Figure 22B displays source level estimates for the ARCTIC FOX during four sustained modes of operation. From the higher curve to the lower curve, these are:

- the tug removing the loaded barge from the dredge to the dump site
- the tug backing down from the barge after tying it off to the dredge
- tug maneuvering to attach to the barge
- tug moving on constant heading without the barge.

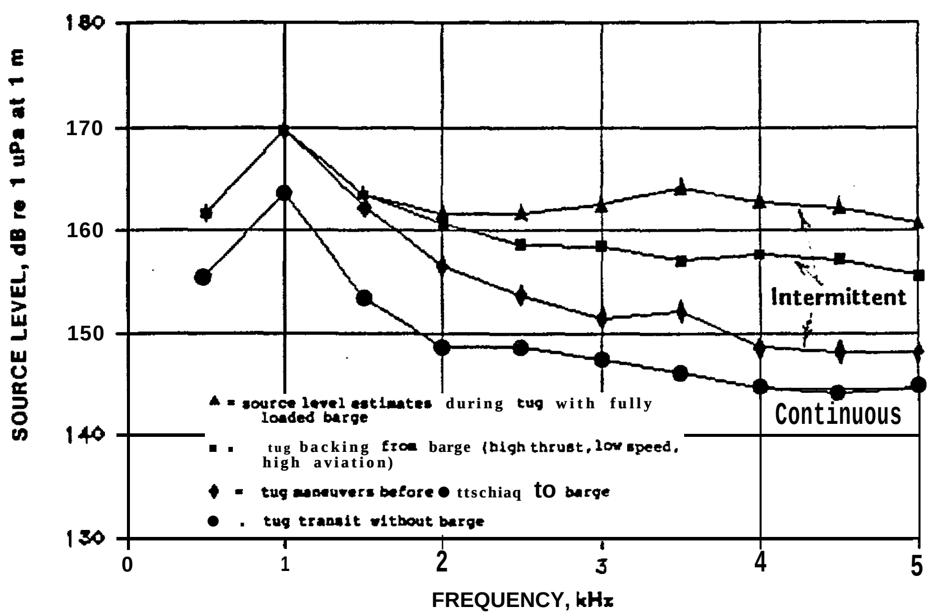
As noted in the previous section, seismic activity prevented third octave band analysis directly, so again, narrowband analysis was employed,. Because the tug noise varies relatively smoothly with frequency, the peak envelope of the measured narrowband spectra was sampled at 500 Hz intervals and these values corrected to third octave band levels by adding 10 log (BW) where BW is the appropriate third octave bandwidth for each center frequency or 0.23(f). Finally, these levels were corrected for the site specific TL to produce the source level estimates displayed in Fig. 22B.

ROBERT LEMEUR Transit

During a visit to the Erik site on August 18, 1986 the signature of the icebreaker/supply ship, ROBERT LEMEUR was recorded at a range of 5.4 km as the vessel made a transit at



A. NARROWBAND SPECTRUM



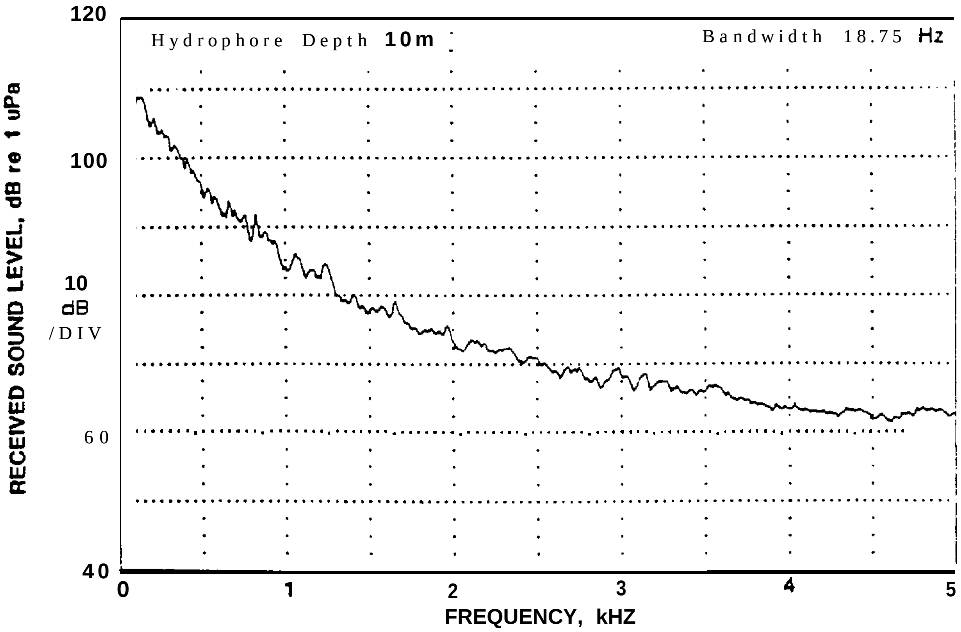
B. SOURCE LEVEL 1/3 OCTAVE SPECTRUM

FIG. 22. RADIATED NOISE SPECTRA FOR TUG ARCTIC FOX, MEASURED AT ERIK SITE, 1985. LEVELS BELOW ABOUT 400 HZ ARE UNKNOWN DUE TO INTERFERENCE FROM SEISMIC PULSES.

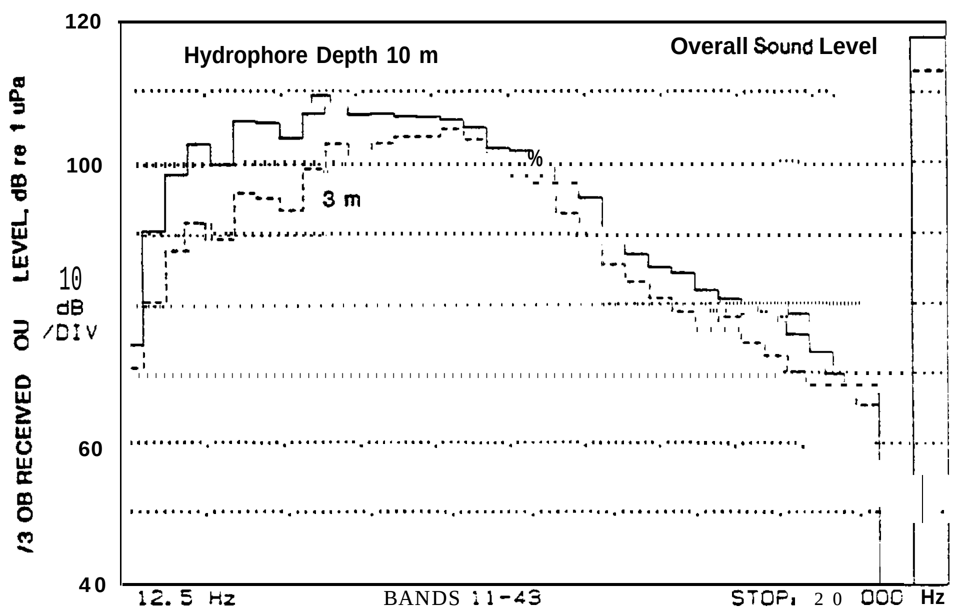
10 kts in open water through the area. The resulting signature information is shown in Fig. 23, The narrow band signature in Fig. 23A does not contain any important tonals because the broadband propeller cavitation noise dominated the output spectrum. Measured transmission loss data were used to correct the analyzed data to obtain an estimated source level for the vessel. The l/3-octave analysis shown in Fig. 23B for the deep hydrophore data provided a source level estimate of 169 dB re 1 μPa at 1 m in the l/3-octave band around 40 Hz, after adjusting the received level given in the figure according to expected acoustic transmission loss (Section 3.3). Deep (10 m) hydrophore data were used for all source level estimates in this report since the shallow hydrophore (3 m) data were influenced by the surface reflection for source frequencies below 300 Hz. The 169 dB figure is comparable to the source level observed in 1985 for the tug ARCTIC FOX during backing operations (see Fig. 22B). Appendix F provides one-third octave band frequency allocations by band number to assist interpretation of the one-third octave band plots shown in this section.

3.2.2 Corona Site - Drillship EXPLORER II, ROBERT LEMEUR (Pushing Ice), KIGORIAK (transit)

The EXPLORER II was located at the Corona site throughout our field measurement season in 1986. Several support vessels were also at this site during the period of on-site measurements. These included two or three supply vessels and two icebreakers. The ROBERT LEMEUR was the active icebreaking vessel with KIGORIAK as the standby vessel. The almost constant vessel movement at the site made it difficult to obtain signatures from individual vessels; however we were able to obtain signatures for the drill-ship during drilling operations and for the ROBERT LEMEUR during icebreaking and ice moving activities. A signature for the KIGORIAK was obtained only under transit conditions.



A. NARROWBAND SPECTRUM



B. 1/3 OCTAVE SPECTRUM

FIG. 23. CONTINUOUS RADIATED NOISE SPECTRA FOR ICEBREAKER, ROBERT LEMEUR DURING AN OPEN-WATER TRANSIT AT 10 KTS, ERIK SITE 1986, RANGE 5.4 KM.

An example of the noise history at the Corona site during a 10-minute period is shown in Fig. 24. This figure is a "waterfall" display of narrow-band spectra taken every 10 sec. The receiving location was 2 km east of the drillship. The initial record is at the bottom of the figure where the spectrum is primarily from the ROBERT LEMEUR moving toward some ice. Two supply vessels were also moving at a range of about 3 km. At the time marked in the figure, marked "C" for cavitation, the ice-breaker was observed to hit the ice and begin to break it up. The significant increase in spectrum levels can be seen with the high frequency energy extending beyond 5 kHz during these times. This increase is caused by the propeller cavitation noise. After each of these ice-pushing episodes, the icebreaker then backed off and repositioned for another pass at the ice. These phases can be seen as the post-"C" periods where spectrum lines are again observed in the signature. This cycle was repeated several times until the ice flow no longer posed a threat to the drillship.

The following subsections describe noise signatures of three specific vessels operating at Corona in 1986.

<u>EXPLORER II</u>

During periods of relative quiet at the Corona site, it was possible to obtain a signature at a range of 1 km from the EXPLORER II. According to information obtained from the operators, the vessel was-drilling at the time. The analyzed received level spectra were corrected to source level using measured TL data. The narrow-band spectrum shown in Fig. 25A shows a dominant tonal at 60 Hz with a secondary tonal at 300 Hz. This 1986 spectrum differs from that obtained by Greeneridge Sciences during EXPLORER II operation at the Hammerhead site in 1985. The BBN analysis of the Greeneridge tape had a dominant tonal at 72 Hz and a secondary tonal at

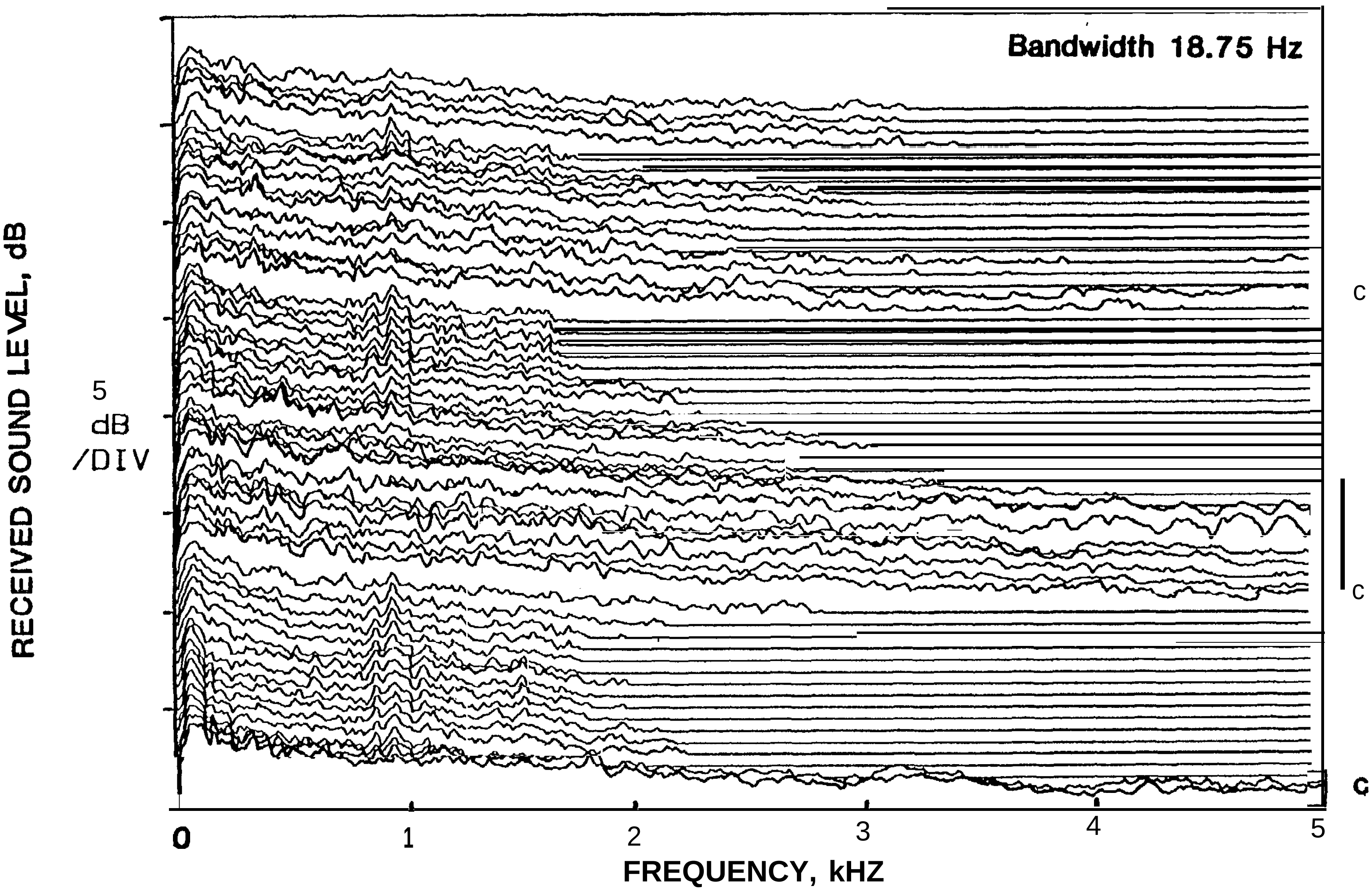


FIG. 24. RADIATED NOISE SPECTRUM SEQUENCE AT CORONA SITE, 1986.
SPECTRUM INTERVAL – 10 SEC., TOTAL TIME INTERVAL – 10 MIN.
"c" INDICATES TIME PERIODS OF HEAVY CAVITATION DURING ICE-WORKING ACTIVITY.

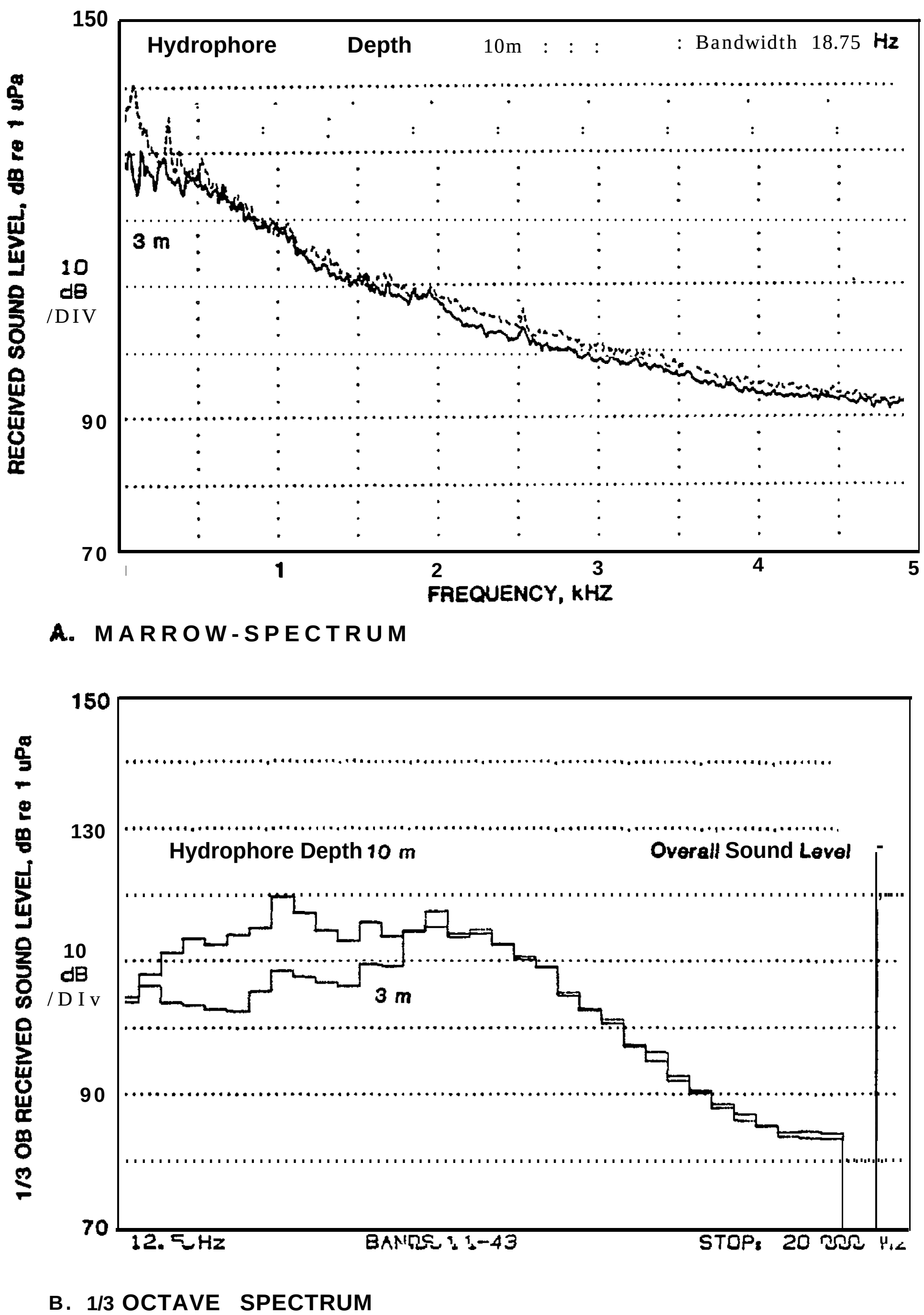
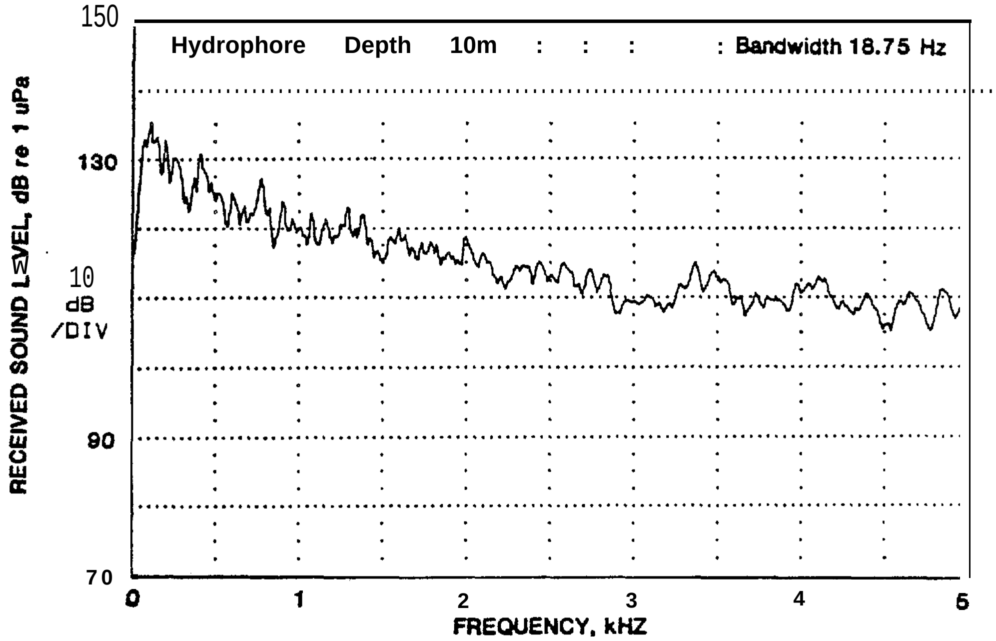


FIG. 25. CONTINUOUS RADIATED NOISE SPECTRA FOR DRILLSHIP EXPLORER II, MEASURED AT CORONA SITE, 1986, RANGE 1 KM.

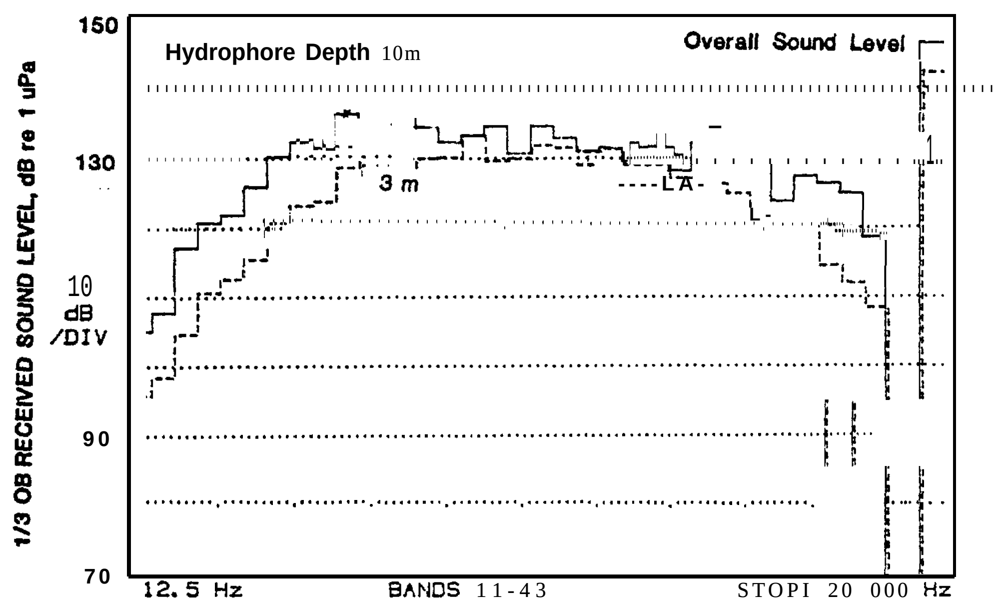
239 Hz (additional information is presented in the Hammerhead site discussion). Moreover, this also differs from an earlier EXPLORER II signature based on measurements in the Canadian Beaufort (Greene 1985), where the dominant tonal was at 278 Hz. Thus the signature of this vessel cannot be considered to remain constant from year-to-year. The variation probably results from changes in the operating machinery. The 1/3-octave spectrum received from the vessel is shown in Fig. 25B. The source level in the 63 Hz band was determined to be 167 dB (re 1 μPa at 1 m) based on transmission loss measurements. This is comparable to the level estimated for the 278 Hz tonal previously reported (Malme et al. 1983). See Appendix F for frequency allocation key band number.

ROBERT LEMEUR Pushing Ice

The ice conditions at the Corona site varied during the 1986 field period from about 7/10 to 1/10 with some heavy flows passing through. As a result the icebreaking activity at the site was sporadic. Several sequences of icebreaker activity were recorded and analyzed to obtain information on the range of noise levels produced. The representative narrowband spectrum shown in Fig. 26A does not show any distinct tonals because the heavy cavitation which occurs is primarily a broadband noise source. This is demonstrated in the l/3-octave spectrum shown in Fig. 26B which shows a basically flat spectrum extending out beyond 20 kHz. A slight peak occurs near 100 Hz with a 1/3 octave band source level of 183 dB (re 1 μPa at 1 m). See Appendix F for frequency allocation by band number. The peak noise level during fluctuating icebreaking activity is therefore the loudest on-site industrial noise signal observed during the study (excluding seismic array sources which were not specific to a single site). The cavitation noise associated with icebreaking activity



A. NARROWBAND SPECTRUM



B. 1/3 OCTAVE SPECTRUM

FIG. 26. INTERMITTENT RADIATED NOISE SPECTRA FROM ROBERT LEMEUR DURING ICEBREAKING OPERATIONS, MEASURED AT CORONA SITE, 1986, RANGE 1.5 KM.

at the Corona site was received during measurements at the Belcher site - over 50 km away.

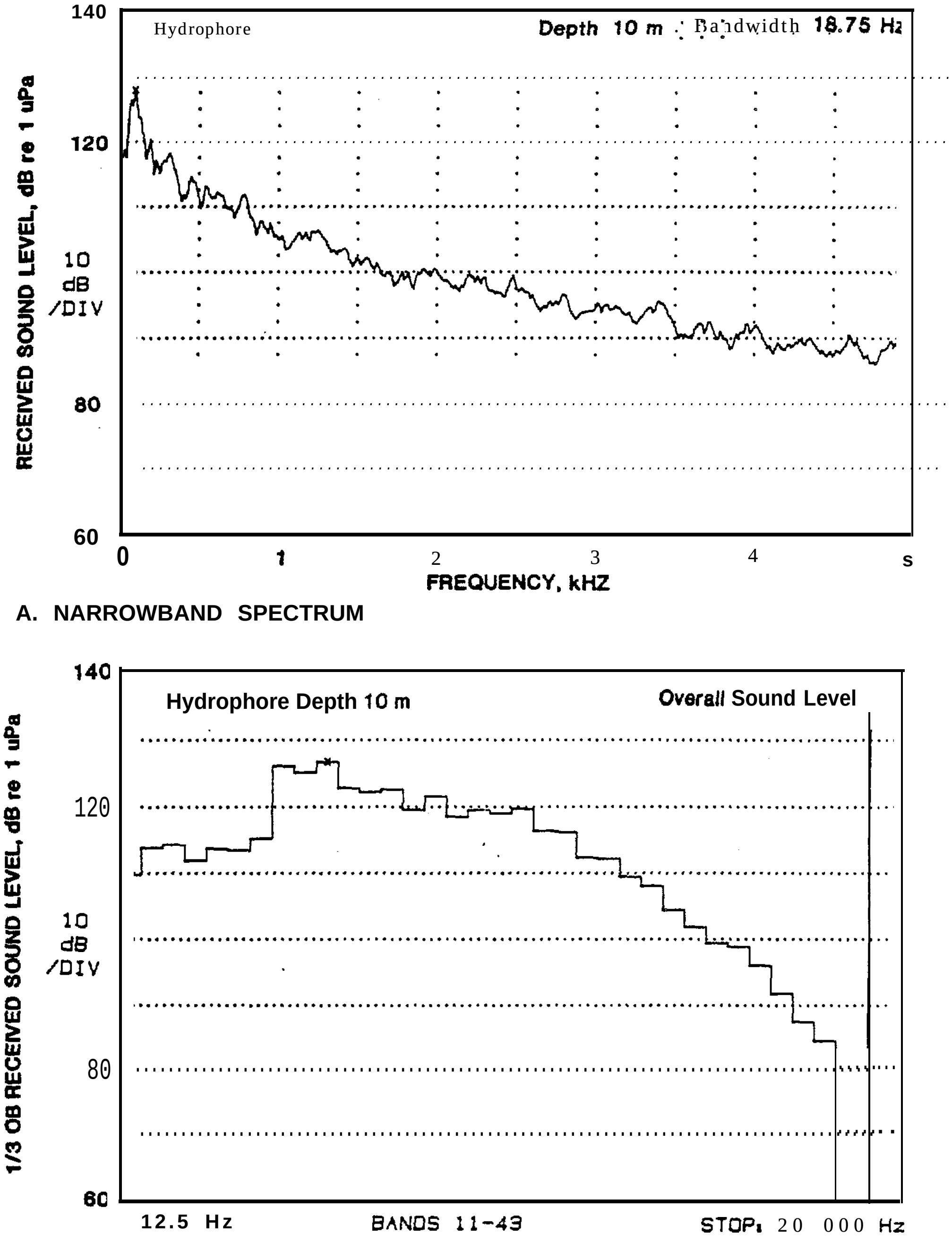
<u>KIGORIAK in Transit</u>

The icebreaker CANMAR KIGORIAK was not actively working ice during the measurement periods at the Corona site but the signature of this vessel was obtained during a 10 kt open water transit at the site. At this speed the propellers are cavitating heavily producing a broad spectrum as shown in the narrowband spectrum of Fig. 27A. A single broad peak can be seen around 87.5 Hz. The l/3-octave spectrum is shown in Fig. 27B where the highest amount of acoustic energy can be seen to fall into the 100 Hz band. The source level in this band is estimated to be 173 dB (re 1 µPa at 1 m). Appendix F provides frequency allocation by band number. The source level for this vessel is slightly higher than that of the ROBERT LEMEUR at the same speed (Fig. 23B). The KIGORIAK is a more powerful vessel than the ROBERT LEMEUR, having a total shaft horsepower rating of 16,800 bhp compared to the ROBERT LEMEUR rating of 9,600 bhp. We were not able to obtain an independent signature for a supply vessel which was free of interference from other sources but the source level and the signature of the ROBERT LEMEUR in open water are expected to be close to those of the supply vessels under similar operating conditions. Typical supply vessels are rated at about 7,000 bhp.

3.2.3 Hammerhead Site - EXPLORER II (1985)

<u>EXPLORER II at the Hammerhead Site</u>

On 27 August 1985, Greeneridge Sciences made a series of measurements of the radiated noise from the drillship EXPLORER II during drilling operations (McLaren et al. 1986). Data were acquired at ranges from 0.1 n.m. (0.2 km) to 5.0 n.m. (9.3 km) to



A. NARROWBAND SPECTRUM

B. 1/3 OCTAVE SPECTRUM

FIG. 27. CONTINUOUS RADIATED NOISE SPECTRA FOR ICEBREAKER KIGORIAK DURING A 10 KT OPEN-WATER TRANSIT AT CORONA SITE, 1986, RANGE 1 KM.

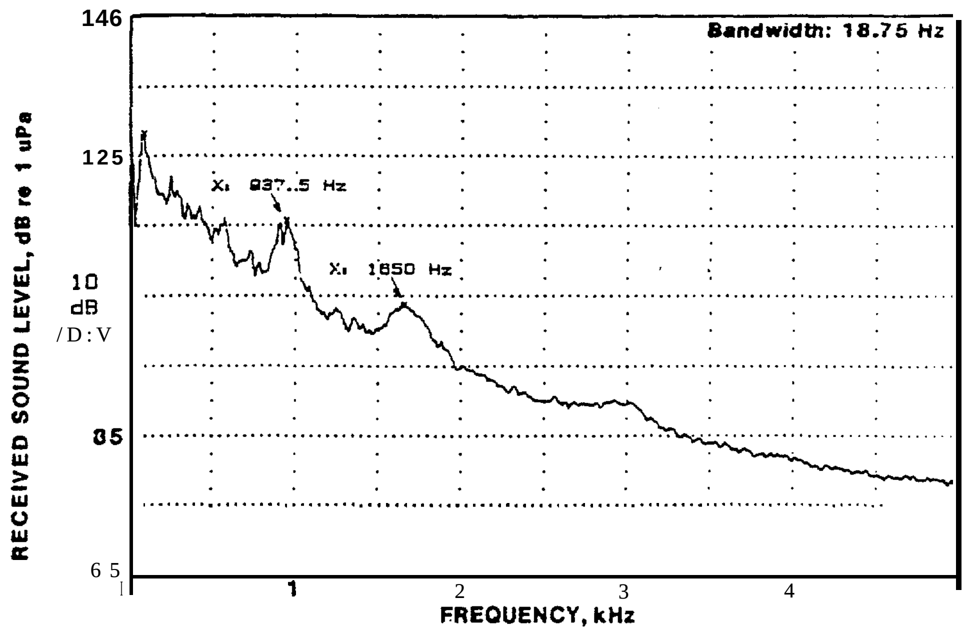
the north of the drillship. The environmental conditions were as follows: 32 m water depth, 5 kt wind speed, clear skies and about 1/10 ice cover. The measurements presented here were recorded at a 9 m depth and analyzed directly from the Greeneridge Sciences tape.

A sample received level spectrum is presented in Fig. 28A, taken at a 1 km range. The dominant radiated noise components are: 1) a reasonably narrowband tonal near 72 Hz (the bandwidth at 3 dB down from the peak equals about 10 Hz), 2) a narrowband tonal at 239 Hz, 3) a broadband energy peak centered at about 920 Hz, and 4) another broadband peak centered at about 1640 Hz. Figure 28B displays a third octave band received spectrum with the bands corresponding to the frequencies noted. In order to estimate the source strength of these components (in the absence of site-specific TL measurements), TL estimates were calculated using the radiated noise measurements and the least-squares error procedure outlined in Sec. 3.3. The TL model analysis derives a least-squares error estimation of the source level. Based on these estimates, the third octave band received spectrum was adjusted for the site-specific TL and the source level estimate was generated. The dominant band was around 80 Hz with a source level of 162 dB (re 1 µPa at 1 m). The two other significant bands were 250 Hz with 161 dB source level and 1 kHz with a source level of 160 dB . Appendix F provides one-third octave band frequency allocations.

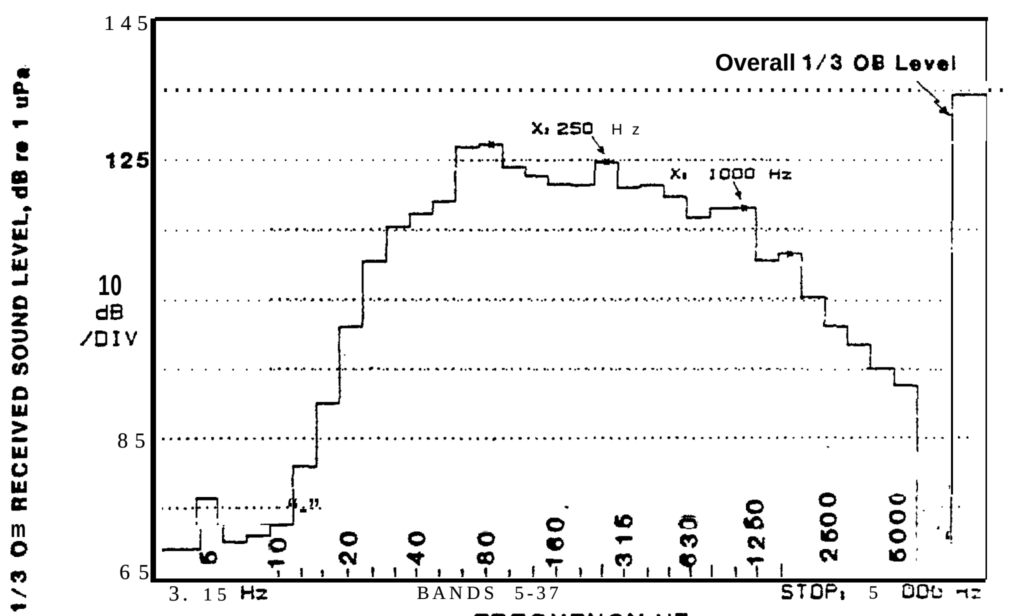
3.2.4 Sandpiper Island - tug operations, drilling activity

Twin Tugs at Sandpiper Island

The transport of heavy materials and equipment to and from artificial islands is carried out mainly by barges, which are either self-propelled or pushed by tugs. On 30 August, 1985, BBN measured the radiated noise from a pair of tugs which were



A. NARROWBAND SPECTRUM



B. 1/3 OCTAVE SPECTRUM

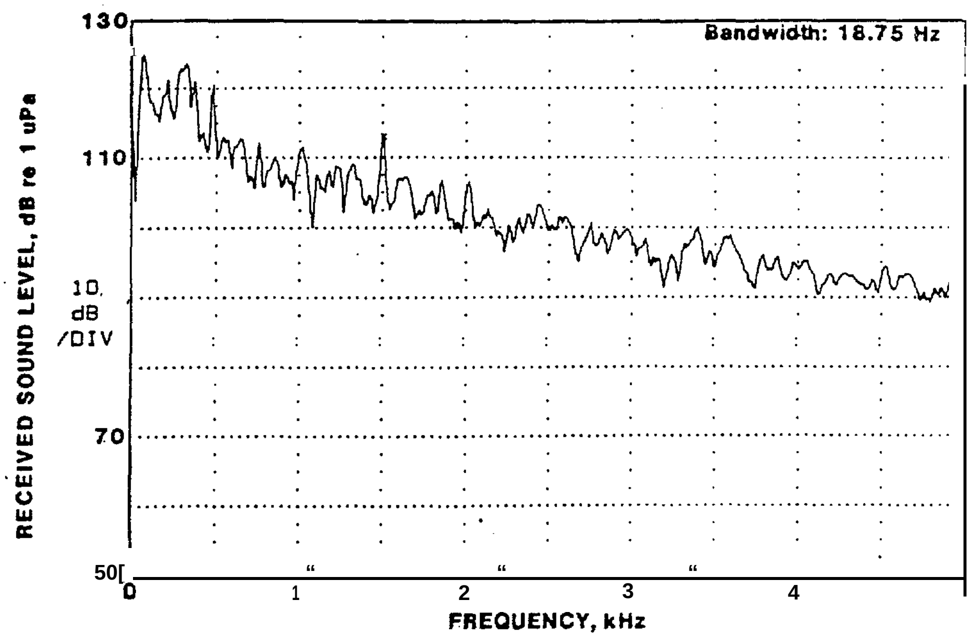
FIGURE 28. CONTINUOUS RADIATED NOISE SPECTRA FOR DRILLSHIP EXPLORER II OPERATING AT HAMMERHEAD SITE 1985, RANGE 1 KM (DATA FROM GREENERIDGE SCIENCES).

keeping a barge pressed against the loading ramp at Sandpiper Island. The tug force against the barge was sustained for at least the six hours while BBN was performing experiments at Sandpiper. Both vessels applied high thrust to the barge and therefore propeller cavitation noise levels were high. On that day, the wind speed was O-5 kt, the sea state was zero, the ice cover was about 1/10, and range was 0.5 km.

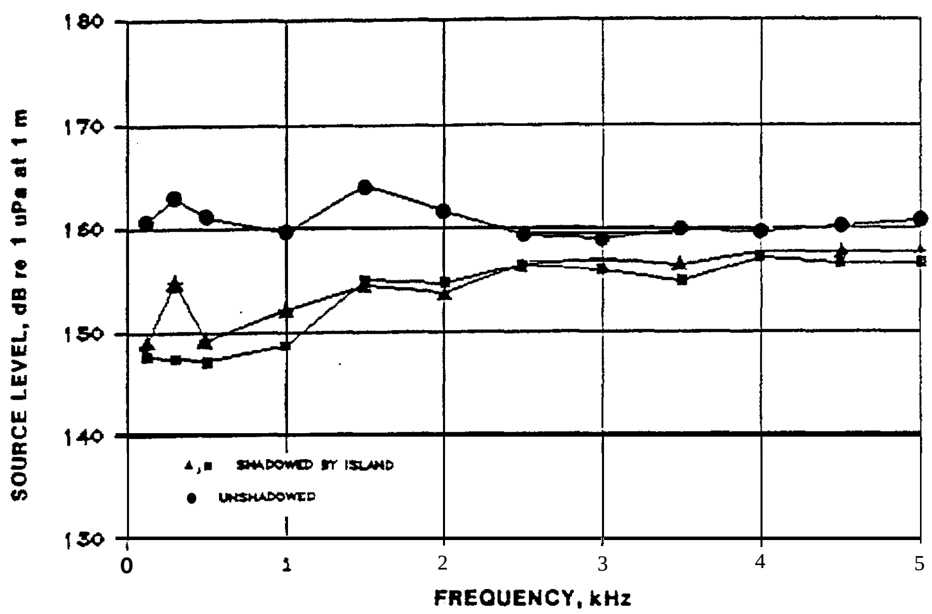
A sample narrowband received level spectrum is shown in Fig. 29A. In general, the radiated noise is broadband in character. The few narrowband components were unstable in both frequency and level. The analysis procedure is much the same as with the tug at the Erik site. A smoothed envelope of the peak spectrum levels versus frequency is sampled at discrete frequencies. The values are then adjusted for the site-specific TL and corrected to third octave band levels. The result is shown in Fig. 29B. Two additional curves are presented in Fig. 29B which show the effect of partial island shadowing as a receiver moves circumferentially around the island. It is important to recognize that this type of industrial noise source may have significant spatial variability.

Drilling Sounds from Sandpiper Island

Greeneridge Sciences measured the radiated noise during drilling operations from Sandpiper Island on 17 October 1985 (Johnson et al. 1986). Data were collected from a bottom mounted hydrophore estimated to be at a range of 0.45 km and from two sonobuoys deployed through the ice at ranges of 2 and 5 n.m. (3.7 and 9.3 km, respectively). The bottom hydrophore was bouyed l-m above the bottom at a depth of about 16 m while the latter two sonobuoy hydrophores were suspended at a depth of 9 m. The weather was overcast, visibility clear, with wind speeds roughly 10 kts and an ice cover of 8/10-10/10.



A. NARROWBAND SPECTRUM



B. SOURCE LEVEL 1/3 OCTAVE SPECTRUM

FIG. 29. CONTINUOUS RADIATED NOISE SPECTRA FOR TUG OPERATIONS AT SANDPIPER ISLAND, 1985 (TWO VESSELS PRESENT).

Figure 30 is a sample narrowband received level spectrum measured by the near-bottom sensor. No significant industry-related acoustic components were observed above about 200 Hz on any of the 3 receivers. Indeed, no man-made noise at all was observed on the 5 n.m. sensor and therefore it is not discussed further. As is obvious from Fig. 30, the dominant tonals are at 20 Hz and 40 Hz. The association of these two tones with drilling was demonstrated by the fact that their levels increased by 6-11 dB and 15-24 dB, respectively, when drilling started (Johnson et al. 1986, p. 50). The lower level tonals at 90, 100 and 120 Hz are not detected at the 2 n.m. sonobuoy and therefore cannot be examined further due to lack of TL data under the high ice cover conditions during these measurements.

For the 40 Hz tonal, we used three data samples at two ranges (6 data points) and applied the least-squares error TL model. We therefore estimated that the source level of the 40 Hz tonal was 145 dB re 1 μPa at 1 m. Because this tonal dominates the third octave band centered at 40 Hz, the source level estimate for the third octave band near 40 Hz is also 145 dB re 1 μPa at 1 m. This appears to be the only significant radiated signal from Sandpiper Island during drilling operations which Greeneridge relates to diesel electric generator operation (see also Johnson et al. 1986).

3.2.5 Seismic survey noise

Seismic survey activities were not specific to any one site in the study area but were evident during our field measurements at least 80% of the time during the field season for both 1985 and 1986. The intensity of the sound produced was sufficiently high to be detectable above the local ambient noise at ranges estimated to be over 100 km in many areas. Seismic survey noise is thus an important contributor to the local noise level at most

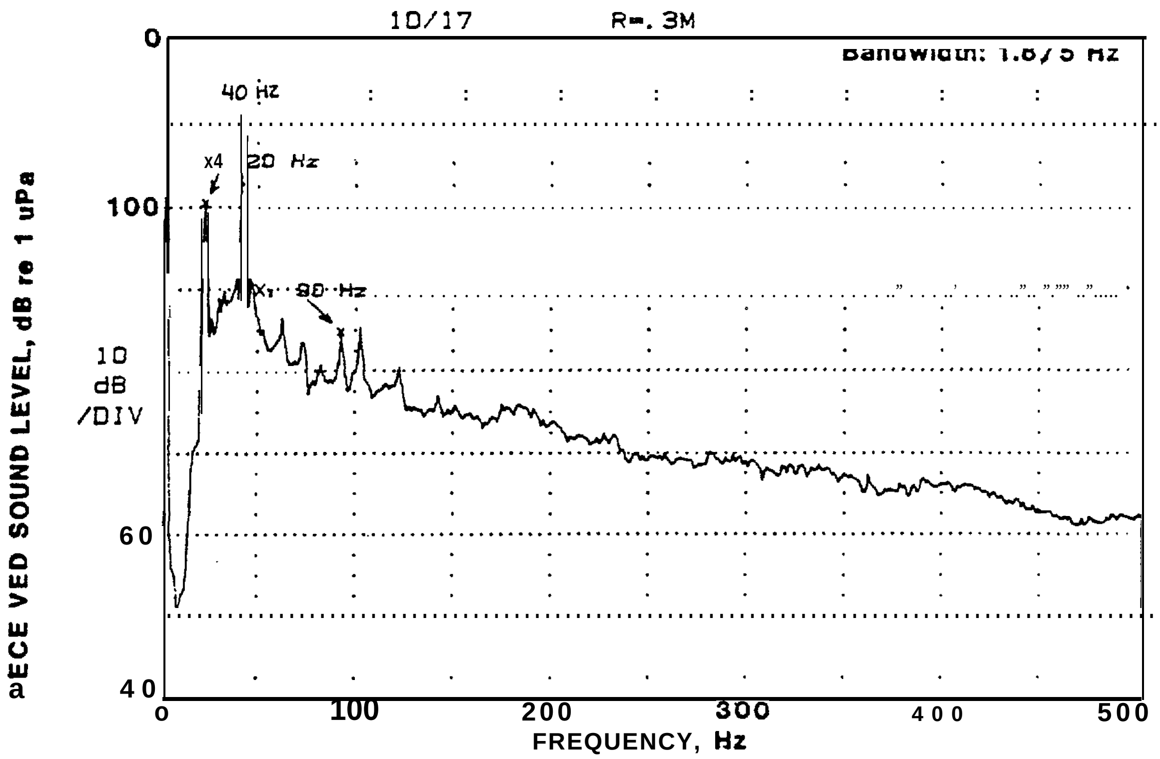


FIG. 30. RADIATED NOISE SPECTRUM FROM DRILLING OPERATIONS ON SANDPIPER ISLAND, 1985 RANGE = 0.45 KM. (DATA FROM GREENERIDGE SCIENCES, INC. cf. Johnson et al. 1986).

of the drill sites in our study. We are, therefore? including this section which contains some representative noise spectra measured during a survey transect made by the WESTERN POLARIS north of the Corona site during the 1986 field season.

Figure 31 shows the pressure waveform and the 1/3 octave spectrum for the seismic array sound measured at a range of 5.8 km from the array. The one-third octave analysis was performed as described in Section 2.2.2.3. The array volume was 1750 cu. in. and the measurements were made on the axis of the array (endfire). The waveform data are presented with two time bases to show the waveform details and the pulse repetition rate. Note that the peak pressure does not occur at the onset of the pulse but rather at about 55 msec after the initial arrival. This is probably a result of the array geometry and the transmission path properties. The peak of the 1/3 octave spectrum can be seen to occur at 50 to 100 Hz at a received level of about 150 dB re 1 μPa. The dashed spectrum in the figure is the background level at the measurement position. At this time the auxiliary generator on the measurement vessel was operating so this spectrum is higher than the local ambient noise. See Appendix F for frequency allocations of band numbers.

Figure 32 shows the results of similar measurements made when the survey vessel had reached a range of 29.6 km. The measurements were again made with endfire geometry. The waveform data show the frequency dispersion which is typical of shallow-water arctic propagation. The upper waveform in Fig. 32A (a time expansion of a single pulse) demonstrates that the high frequencies in the seismic pulse arrive at the receiving position before the low frequencies. The low frequencies can be seen to reverberate for a long time and do not entirely die away between pulses. This is shown in the l/3-octave spectrum in Fig. 32B where the received level spectrum is seen to have two peaks, both

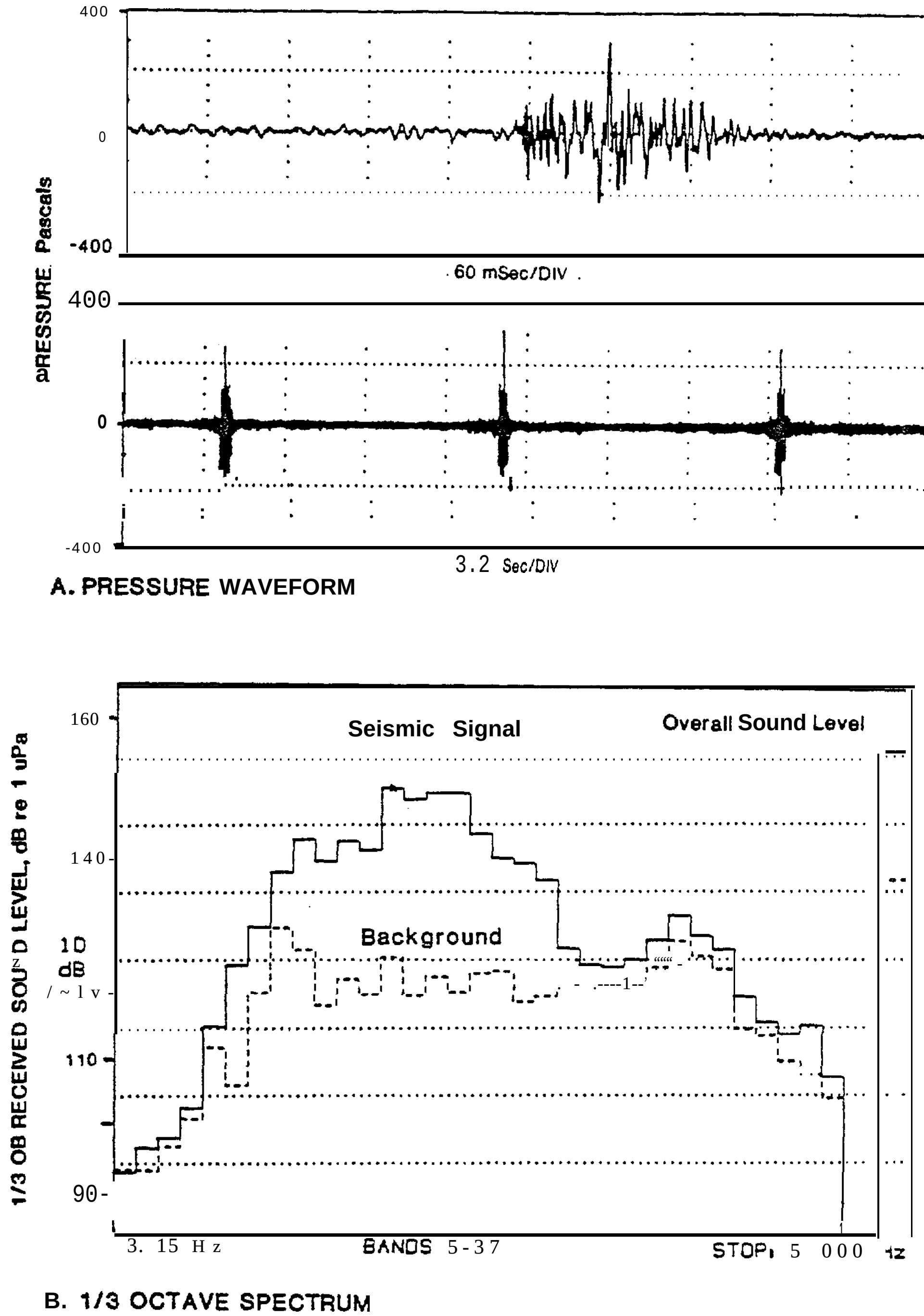


FIG. 31. PRESSURE WAVEFORMS (A) AND RADIATED NOISE SPECTRUM (B) FOR AIR GUN ARRAY SEISMIC SURVEY OPERATIONS NORTH OF CORONA SITE, 9/4/86, RANGE 5.8 KM.

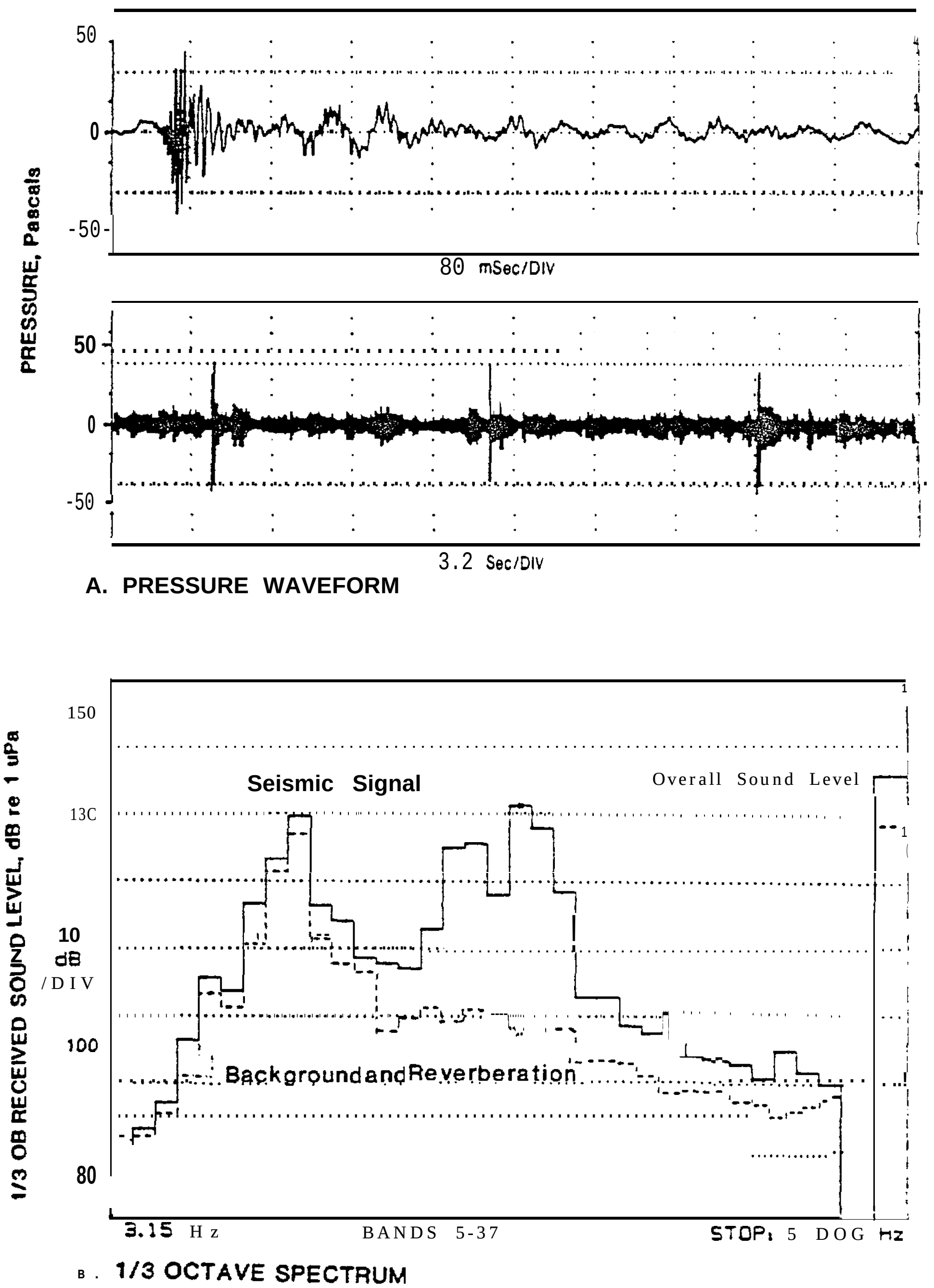


FIG. 32. PRESSURE WAVEFORMS (A) AND RADIATED NOISE SPECTRUM (B) FOR AIR GUN ARRAY SEISMIC SURVEY OPERATIONS NORTH OF CORONA SITE, 9/4/86, RANGE 29.6 KM.

at a level of about 130 dB re 1 μPa. The low-frequency peak at 20 Hz is the long duration reverberation and the high frequency peak at 100 to 200 Hz is the transient pulse energy. The ship's auxiliary generator had been shut down during this measurement so the dashed spectrum represents the local ambient plus the seismic signal reverberation as measured between the seismic pulse arrivals. An overall broadband peak source level at endfire of 228 dB re 1 μPa at 1 m was estimated for this array based on an analysis using the TL model and the least-squares procedure method in Sec. 3.3*

3.2.6 Summary of industrial noise source measurements

The source level data obtained from the study are summarized in Table 7. These data should be considered as examples of the acoustic output for the type of source measured. More measurements of similar source types are required to obtain general mean values for a given class of source.

3.3 Acoustic Models and Sound Propagation Characteristics

Sound transmission in shallow water is highly variable, since it is strongly influenced by surface conditions, by acoustic properties of the bottom material, and by sound speed variations in the water column. Variations in the temperature and salinity of the water column cause sound energy paths to be bent (refracted) downward or upward resulting in varying energy loss depending on the extent of interaction with the bottom and surface boundaries in addition to the attenuation due to geometric spreading.

When the sound wavelengths (λ) are comparable to the water depth (H) ($0.25 < H/\lambda < 2$), the sound energy is considered to be spreading cylindrically in a two-dimensional horizontal waveguide. This is the condition where acoustic mode theory is appropriate. Mode theory predicts that if the water depth is less

TABLE 7. SOURCE LEVEL DATA SUMMARY, BEAUFORT SEA DRILL SITE MEASUREMENTS 1985, 1986.

			AVERAGE LEVEL IN dB re 1 µPa AT 1 M IN 1/3-OCTAVE BAND CENTER FREQUENCIES FOR SIGNIFICANT COMPONENTS (Hz)																		
Source	Site	Date	40	63	80	100	125	160	200	250	315	400	500	630	800	1.0K	1.25	1.6	2.0	3.15	4.0
Dredge																					
ARGILOPOTES	Erik	9/85	——— NO DATA ———							162		159			158		158				
Tug Activities																					
ARCTIC FOX (Man.)	Erik	9/85	——— NO DATA ———										162			170		163	162	163	163
2 Tugs (Stationary)	Sand.	8/85					161			163			161			160		164	162	159	160
Vessel Transit																					
ARCTIC FOX	Erik	9/85	——— NO DATA ———										156			164		153	148	147	145
R. LEMEUR	Erik	8/86	169				164				163										
KIGORIAK	Corona	9/86		173			173		168		166				162						
Icebreaking																					
R. LEMEUR	Corona	9/86					183			182		180				180		177			
Drillship																					
EXPLORER II	Hamm.	9/85			162					161						160					
EXPLORER II	Corona	9/86		167				162			160										
Drilling on Art. Is.																					
Sandpiper	Sand.	9/85	145																		
Seismic Survey																					
WESTERN POLARIS		9/86	200*				209*		201*												

*Peak level in 1/3-octave band during pulse.
[The overall (broadband) peak source level for this array at end fire has been calculated to be 228 dB re 1 µPa at 1 m).]

than $\lambda/4$, no acoustic energy can propagate. In many cases, however, the bottom consists of water-saturated sediment and is not a discrete reflecting boundary for all of the sound energy. Here the propagation of low frequency sound energy involves the bottom as an extension of the water column. Thus, hard sub-bottom layers under the upper sediment bottom often provide the dominant reflecting surface for low frequency sound energy.

At high frequencies or in deeper water where the water depth is large compared with the sound wavelengths ($H/\lambda > 5$), acoustic ray theory is applicable and acoustic energy can be considered to propagate along paths that are usually multiply reflected from the surface and bottom. A range (R)-dependent spreading loss of 15 Log R, which is midway between the cylindrical spreading loss of mode theory (10 Log R) and the spherical spreading loss (20 Log R) of unbounded deep water, has been found to be generally appropriate in shallow water when sound speed gradients are either neutral or downward refracting. When gradients are upward-refracting so the bottom reflection losses are minimized, a 10 Log R cylindrical type of sound propagation is appropriate, even though ray theory (not mode theory) is relevant.

Transmission Loss Models

Several analytic computer-based models have been developed to predict acoustic transmission loss characteristics using measured sound speed profiles, bottom-loss parameters, and surface scattering effects. These models have been designed primarily for Navy applications (e.g., Weinberg 1985) in deep water and have limited capabilities for handling all of the significant environmental parameters that influence shallow water sound propagation. The major modeling difficulties occur at low frequencies for sites with a sloping, multi-layered bottom and strong sound velocity gradients. As a result, we have developed a semi-empirical approach which uses sound velocity and sound propagation data obtained from *in-situ* measurements combined with computer-based analytic models to provide a general sound propagation characteristic for a specific area. The following discussion covers the development and application of this procedure which has been used in obtaining the sound transmission characteristics presented in this report.

3.3.1 Analytic sound propagation model

The shallow-water environment is very complex from the acoustical viewpoint. A complete specification would involve descriptions of

- the sound speed profile in the water,
- bottom topography,
- bottom stratigraphy as function of location,
- surface conditions (roughness, ice) .

Elaborate computer programs are required to use this information in a prediction of transmission.

Fortunately, since such detailed information is rarely available, it has been found possible to make reasonable predictions from simple formulas in the typical case where the sound speed is nearly independent of depth and the bottom slopes uniformly and gradually. These formulas have been developed and tested by D.E. Weston of the British Admiralty Research Establishment (Weston 1976).

In the simplified formulas, there are five parameters:

1. dominant frequency
2. water depth at the source
3. bottom slope along track

4,5. two parameters to describe the reflection loss of the bottom.

In these formulas, the term for the reflection loss (RL) in decibels for reflection of a plane sound wave incident at a grazing angle ϕ is taken to be:

$$RL\ (dB) = 4.34\ b\ \sin\phi,\ \text{if}\ \phi < \phi_c,\ \text{or}$$

$$RL > 20\ dB,\ \text{if}\ \phi > \phi_c. \tag{1}$$

The two parameters to be estimated are b and the critical angle ϕ_c.

Because of bottom stratigraphy, the bottom reflection loss parameters are found to vary with frequency (Smith 1986). The explanation is simple. A typical bottom in shallow water consists of a layer of sand or silt overlying rock. If the layer is thin, the sound is effectively reflected off the rock; if the layer is thick, the sound is effectively isolated from the rock. Calculations indicate that the transition occurs when the surface layer thickness equals about one-half wavelength of sound.

Typical values of the bottom loss parameters are

sand/silt: $b = 2$, $\sin\phi_c = 0.4$
hard rock: $b = 0.4$, $\sin\phi_c = 0.7$.

Soft rock, such as limestone or chalk, can be very absorptive because of transmission of energy in the shear wave. The values of the parameters b and ϕ_c are very sensitive to the value of the shear wave speed (Smith 1986).

Weston's formulas for transmission loss divide the transmission path into four regions, each of which has a characteristic range dependence. The regions are, in order of increasing range,

a. spherical spreading, where bottom-reflected rays are steeper than the critical angle;

b. a transitional, cylindrical spreading region;

c. a "mode stripping" region, wherein energy striking the bottom at steeper angles is attenuated more rapidly than that at shallower angles; and

d. the "lowest-mode" region, wherein only the fundamental mode carries significant energy.

Only in the last region is transmission dependent on frequency, so long as the sand layer is either thin ($d < \lambda/2$) or thick ($d > \lambda/2$) at all frequencies of interest. (See discussion of bottom reflection loss, above.)

In addition to water depth and bottom composition, the slope of the bottom is also important in determining transmission loss in shallow water. For sound transmission from a shallow region to deeper water, the increasing depth permits the sound energy to spread out over a larger volume than would have been available if the depth had remained constant. This results in a reduction in sound level. On the other hand, the increase in depth results in fewer bottom and surface reflections and thus less energy loss per kilometer. For most bottom types, the reduction in reflection loss has the strongest influence so the net effect of a positive bottom slope (increasing depth with increasing range) is lower transmission loss. This effect is most pronounced when neutral or upward refracting sound speed gradients exist. For these conditions sound transmission becomes ducted and is no longer influenced by bottom reflection loss.

For sound transmission into a decreasing depth region (negative bottom slope), the decrease in available volume for the sound energy would normally cause the sound level to be higher than it would be at the same range in a constant depth region. However the number of surface and bottom reflections increases as the depth decreases. This causes the sound level to drop. This effect again usually predominates and the transmission loss becomes higher as sound propagates upslope. As the depth decreases, a depth is reached where there is a transition from multimode to single mode propagation. This usually results in a shift from a 15 Log R to a 10 Log R spreading loss characteristic. The attenuation per kilometer is determined primarily by the bottom material and may be quite high for soft bottom sediments. As water depth continues to diminish, there will be a point when effective propagation to long distances for frequencies of interest is not efficient (transmission loss becomes very high).

The Weston formulas noted previously apply to both positive and negative uniform bottom slopes as well as to the constant depth case. A short computer program written in BASIC was designed by P.W. Smith, Jr. at BBN which incorporates these formulas, yielding a value of transmission loss (dB re 1 m) when given a value of range. This model, which we have called the Weston/Smith Model, does not incorporate refraction effects produced by sound velocity gradients and is appropriate for conditions where gradients are small or neutral. Within this limitation, the model has been found to provide good predictions in shallow water conditions and has the advantage of being able to run on small computers. A listing of this program is given in Appendix C.

The sound velocity profile (SVP) data obtained during the field periods from late August to mid-September in 1985 and 1986 showed that conditions ranging from downward-refracting to upward-refracting occurred from site-to-site. Moreover, data obtained by personnel aboard the POLAR STAR in mid-October 1986 near several of the sites showed that strong surface duct (upward-refracting) conditions existed at that time. A wide range of sound transmission conditions ranging from downward-refracting (high-loss) through neutral to surface-duct (low-loss) would therefore exist during the whale migration period near the study sites. We therefore had to devise a way of removing the effects of the strong sound refracting gradients from the transmission loss (TL) data to obtain an unbiased estimate of the sound transmission characteristics at each site. This was done using the Multipath program of the Navy Generic Sonar Model (Weinberg 1985).

The Multipath Model

The Generic Sonar Model is a collection of computer programs which are designed to provide sonar system developers with a comprehensive modeling capability for evaluating the performance of sonar systems and investigating the ocean environment. This model is typically run on a VAX Model 11/780 computer using Fortran IV-PLUS. Most of the programs are designed for use in deep water applications, but one of the sound propagation models was found to be suitable for the water depths and frequency range of interest at the Beaufort Sea study sites. This model, called the “Multipath Expansion Eigenray Model”, is based on a horizontally stratified ocean with range-independent depth and sound velocity parameters. It computes the total acoustic energy transmitted from a source to a receiver by all of the sound rays that intersect the receiver location (eigenrays). In doing this, refraction and reflection losses are accounted for by incorporating measured or predicted SVP, and bottom loss data. A model for prediction of surface scattering loss is also included.

The Multipath Model was used to obtain an estimate of the variation in transmission loss characteristics that would occur when the sound velocity gradients prevailing at a given site during the transmission loss measurements changed to a neutral condition. The information obtained from this analysis was used to remove the bias due to prevailing strong gradients from the measured transmission loss data. The adjusted data were then analyzed using the simpler Weston/Smith Model to obtain an unbiased set of site-specific bottom loss parameters.

The Multipath Model requires a table of bottom loss data in addition to a table of sound velocity versus depth as part of the input. The bottom loss data were estimated from known bottom composition and modified as required to have the transmission loss calculated by the program to approximate the measured transmission loss data. When these results were satisfactory, a neutral SVP based on the predominant sound velocity evident in the measured data was substituted in the program for the measured sound velocity data and the program was rerun. The differences in transmission loss versus range were then determined for the two sound velocity conditions. This procedure was repeated for both downward-refracting and surface-duct conditions and for all test frequencies. A series of transmission loss correction tables were obtained which were then applied to the measured data to estimate the received levels that would be expected under neutral SVP conditions. The corrected data were then used in a two-parameter least-squares analysis using the Weston/Smith Model to obtain best-fit estimates of the site-specific sound transmission parameters.

3.3.2 Analysis to obtain site-specific sound transmission parameters

A computer-implemented automatic least-squares analysis procedure was used to derive the parameters of the best-fit transmission loss curve for each set of data. The procedure may be summarized by the following equations:

A calculated sound level at a given range is obtained using the Weston/Smith Model described in Appendix C with assumed values of source level and bottom parameters as shown in Eqn. (2)

$$L_c(r) = Ls' - TL(r(n),b,\sin\phi_c) \quad \text{dB re 1 uPa} \tag{2}$$

where L_s' is the effective source level, or

$$L_s' = Ls + An \quad \text{dB re 1 uPa at 1 m} \tag{3}$$

Here Ls is the calibrated source level and An is the local anomaly caused by bottom and surface reflections. The error between the calculated and measured sound level at range r(n) is

$$ER = L_r(r) - L_c(r) \quad \text{dB re 1 uPa} \tag{4}$$

where $L_r(r)$ is the sound level observed during the transmission loss measurement. The least-squares procedure requires that the calculated curve be matched to the data set so that the mean square error between the data points and the calculated points as a function of range is a minimum for a given data set (test frequency in this case). A computer program was designed to automatically find a minimum by using the rms error equation:

$$E_{rms} = \left(\frac{1}{n}\sum_{r=1}^{n} ER^2(r_n)\right)^{1/2} \tag{5}$$

The rms error of Eqn. (5) is recalculated for successive changes in values of b and An until a minimum is reached. Values of $\sin\phi_c$ are entered manually since the dependence on this parameter is not very strong.

The output of this two-stage procedure using both the Multipath Model and the simpler Weston/Smith Model is, for each site and frequency, a set of estimated values of An, b, and $\sin\phi_c$ which are independent of the effects of sound velocity gradients and of the water depth.

3.3.3 Sound propagation measurement results

Introduction

This section contains a summary of the transmission loss measurement results from all six sites designated by the MMS. TL data were obtained at five sites in 1985 (Table 2). Five of the sites were also visited during the 1986 field period (Table 3) including three (Belcher, Erik, and Sandpiper) that were measured during the 1985 field period. Data were not obtained at the site furthest west (Orion) during 1986 because of a period of strong winds when measurements were planned for that area. The goal of the transmission loss measurements was to obtain site specific data to permit estimation of the range of influence of industrial sources operating at the sites. Data were obtained and analyzed using swept-frequency signals in six 1/3-octave bands from 100 Hz to 4 kHz. (See Section 2.2 for details.) Representative results for 100 Hz and 1 kHz are presented in the following discussion. Complete tables of transmission loss characteristics for all sites and their estimated variation with changes in sound transmission conditions are presented in Appendix C.

Belcher Site

Belcher was the deepest (55 m) and most easterly study area. It was ice-free during the measurement periods in both 1985 and 1986. The sound velocity profile (SVP) data showed that a downward refraction condition existed during the transmission loss measurement period in both years (curves 1 and 2 in Fig. 33). This would cause the measured transmission loss to be higher than under neutral gradient conditions. In contrast, the SVP data obtained in mid-October during the POLAR STAR cruise (curve 3) show a very pronounced surface duct condition where sound transmission at high frequencies would not be influenced by bottom reflection losses. At low frequencies where the duct was not deep enough to trap the longer wavelength energy, the local bottom loss would continue to influence the transmission. However, the general transmission loss would be less than under neutral gradient conditions. The conditions in October 1986 were the result in part of an unusually strong eastward intrusion during September-October 1986 of warm Bering Sea water at sub-surface depths near the shelf break (Fissel et al. 1987). The late season cooling of the surface water before freeze-up also contributes to the establishment of the surface duct.

This wide variation in the SVP was observed within the period when the bowhead whale migration normally occurs. Thus it is important to be able to estimate the variation in transmission loss which would result from the changes in SVP. The procedure using the Generic Multipath Model described in the previous section was used together with the Weston/Smith Model to obtain this estimate. The results are shown in Fig. 34 which gives the "best-fit" transmission loss characteristics for 100 Hz and 1 kHz at the Belcher site. Data were obtained in 1986 along eastward and northward measurement tracks out to a range of 22-24 km. Using the Weston/Smith model to fit these data we can then extrapolate the transmission loss characteristic out to 50 km with acceptable error bounds.

The easterly transmission loss curve for 100 Hz in Fig. 34A can be seen to be not influenced very much by the measured range of sound velocity gradients. The analysis procedure did not show any significant influence at 100 Hz for downward refraction conditions and only a slight influence for surface duct conditions.

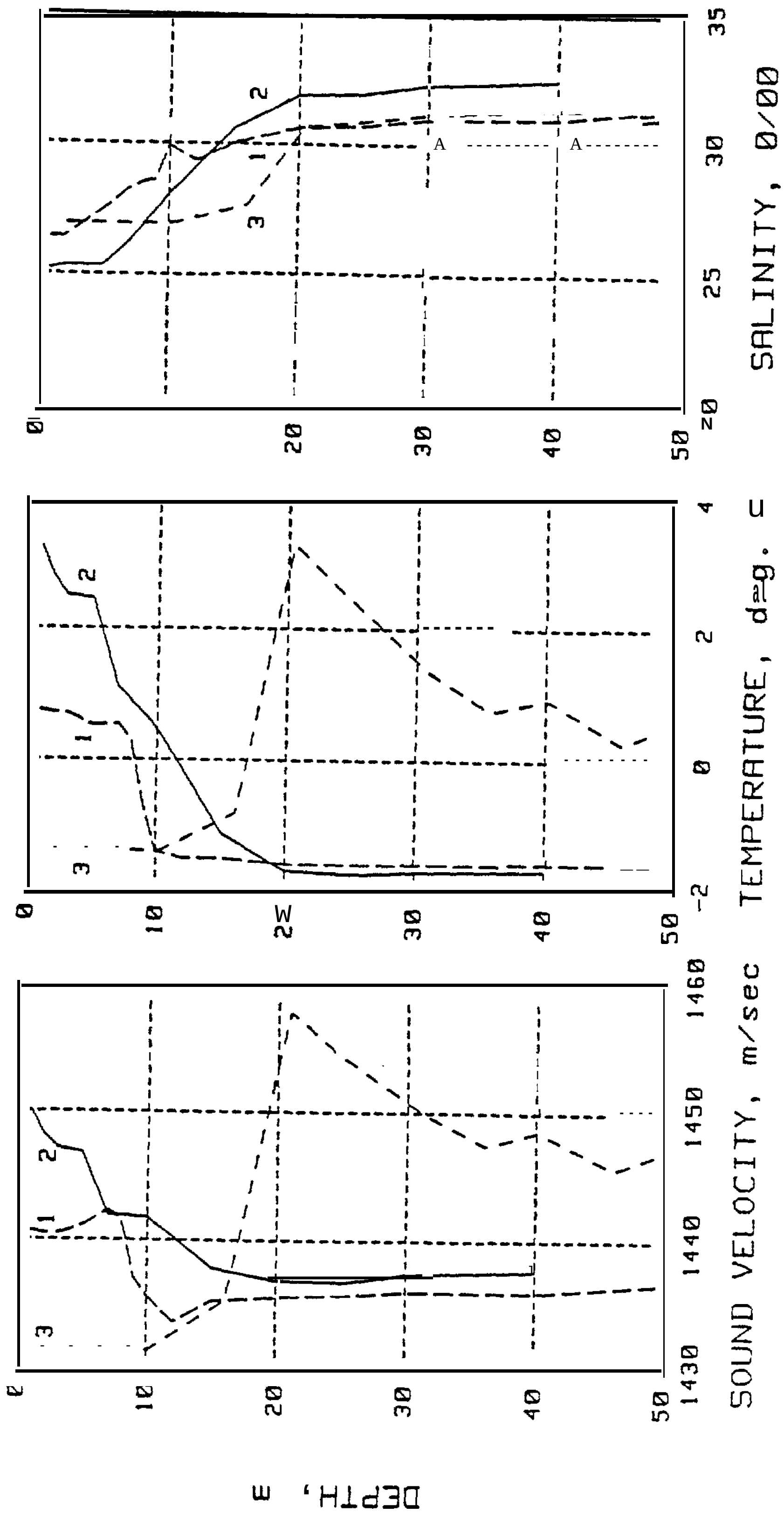
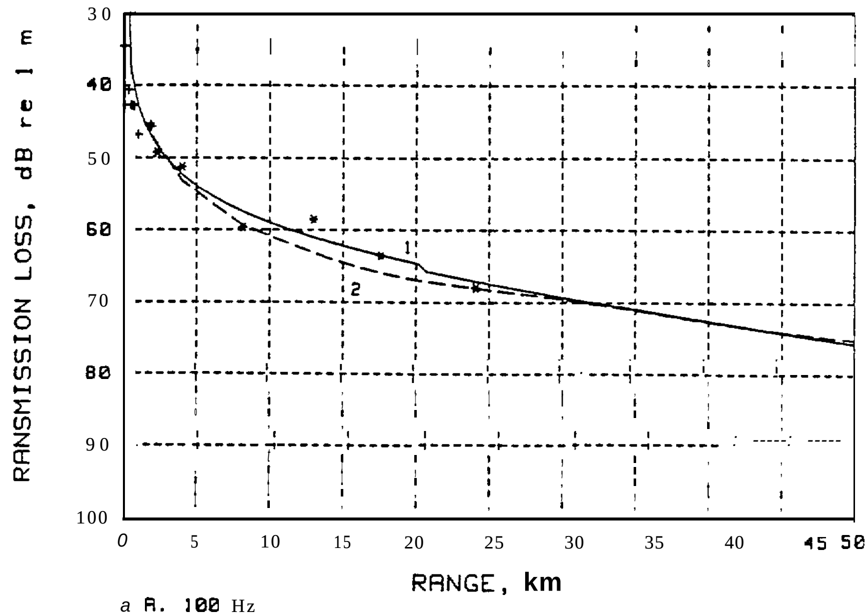
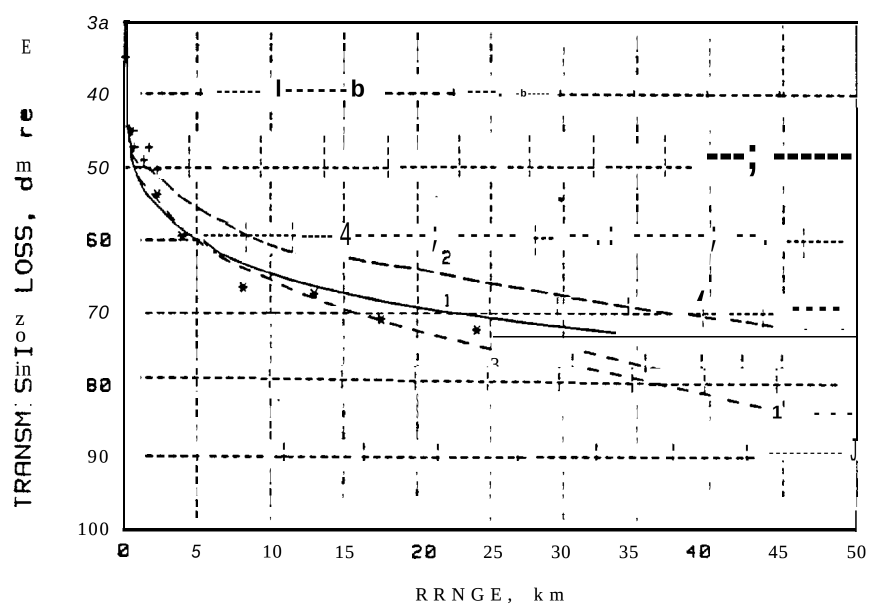


FIG. 33. BELCHER SITE, ENVIRONMENTAL DATA
1 - 9/10/85, 2 - 9/7/86, 3 - 10/13/86 (POLAR STAR).



a. 100 Hz



B. 1 kHz

FIG. 34. BELCHER SITE, EASTWARD TRANSMISSION LOSS CHARACTERISTICS: 1 - NEUTRAL SVP, 2 - SURFACE DUCT, 3 - DOWNWARD REFRACTION, + 1985 MEASURED DATA, * 1986 MEASURED DATA.

At 1 kHz (Fig. 34B) a more significant effect can be seen. Here the expected range of SVP conditions is estimated to result in a change of about 12 dB in transmission loss at 50 km, i.e., from -9 to +3 dB with respect to TL under neutral SVP conditions.

Since the Belcher site is located within the fall migration corridor of bowhead whales (Fig. A.1 in Appendix A), it is necessary to consider the directional dependence of the TL characteristics. The general slope of the bottom toward the north and northeast is expected to cause the TL to be lower in those directions and higher in the southerly direction toward the coastline. This expected trend was investigated by obtaining TL data for measurements to the north of the Belcher site as well as data from measurements to the east.

The 100 Hz and 1 kHz measured data from the north TL measurements at Belcher, uncorrected for SVP effects, are shown in Fig. 35. The best-fit Weston/Smith characteristics are also shown. These data are influenced by the rapid change in slope which occurs at a range of 18 to 20 km north of the Belcher site. As described earlier in Sec. 2.2.2, the TL measurement procedure employed a fixed recording buoy and a moving projector. In obtaining the north TL data at Belcher the buoy was located 22 km north of the site where the water depth was 91 m. The bottom sloped upward toward the Belcher site so that the source moved from deep water into progressively shallower water as the data were obtained. As a result the TL characteristic has a steeper initial drop than it would if the data were taken in the reverse order with the source fixed at the site where the depth is 55 m, with the receiver moving off to the north. To correct for this effect, the east TL data which were obtained for a nearly constant depth of about 55 m, were depth-averaged with the north data so that east data also apply to the north out to a point where the bottom begins to slope signifi-

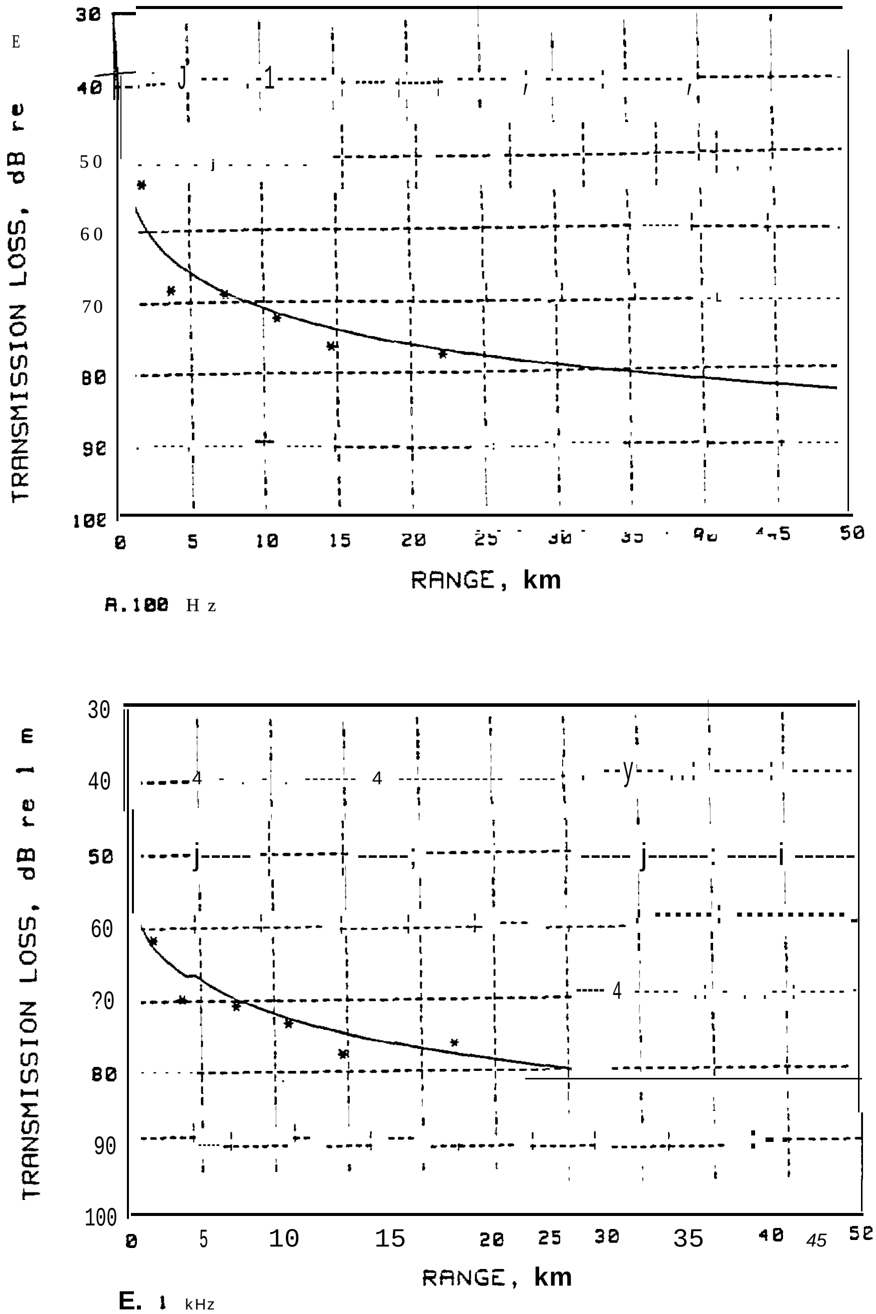


FIG. 35. BELCHER SITE, NORTHWARD TRANSMISSION LOSS CHARACTERISTICS (UNCORRECTED FOR GRADIENT AND BOTTOM SLOPE EFFECTS). * 1986 MEASURED DATA.

cantly, whereupon the north TL data were factored in as the depth increased.

The resulting composite characteristics were also corrected for SVP effects and the best-fit Weston/Smith parameters determined. The results are shown in Fig. 36 for 100 Hz and 1 kHz. The TL characteristics for 100 Hz were not expected to change significantly for the range of SVP conditions given so no additional curves are shown in Fig. 33A. The range of estimated TL variation is shown in Fig. 33B for 1 kHz. Comparison of Fig. 31 and Fig. 36 shows that the TL is about 8 dB higher at 50 km to the north than at 50 km to the east, probably as a result of the increase in water depth, since the bottom loss parameters are similar.

Erik Site

The Erik site is located in somewhat shallower water (40 m) than Belcher. The site was ice-free during the 1985 field period but had varying amounts of ice-cover during the 1986 period. The SVP data in Fig. 37 for 1985 (curve 1) showed a shallow surface duct above 5 m with a possible weak sound channel at a depth of 10 to 25 m. The data obtained in 1986 (curve 2) had approximately neutral gradients, largely as a result of strong winds causing mixing conditions prior to the TL measurement period. The data reported for this area by the POLAR STAR for mid-October 1986 (curve 3) showed a strong surface-duct, again attributable to the unusually strong intrusion of warmer Bering Sea water (Fissel et al., 1987) and cooling of the surface water. We expect that downward-refracting gradients would normally be found at this site during the beginning of the whale migration period - similar to those observed at Belcher - but were not seen because of the specific weather patterns existing at the times of the site visits.

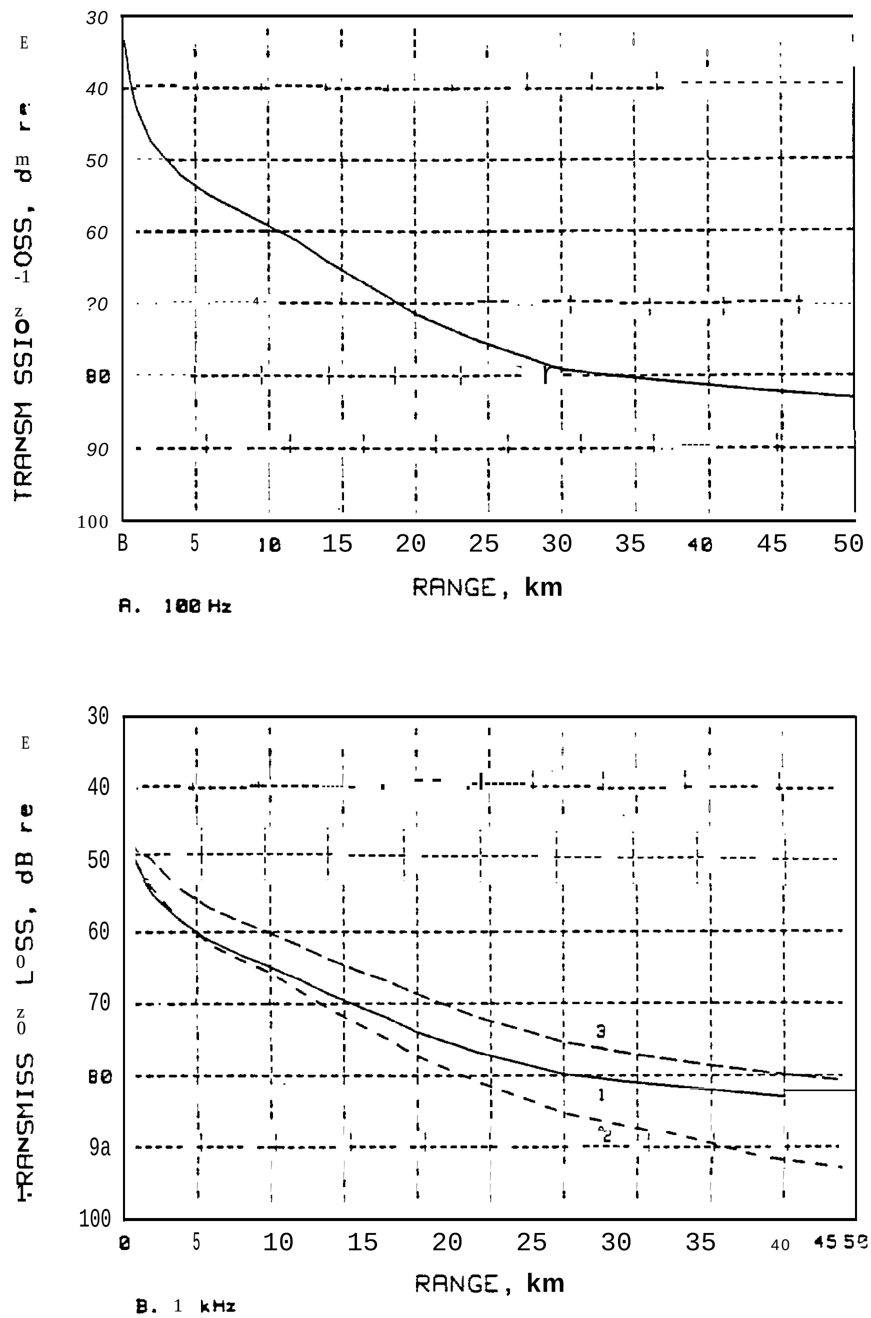


FIG. 36. BELCHER SITE, NORTHWARD TRANSMISSION LOSS CHARACTERISTICS (CORRECTED FOR GRADIENT AND BOTTOM SLOPE EFFECTS). 1 - NEUTRAL SVP, 2 – SURFACE DUCT, 3 - DOWNWARD REFRACTION.

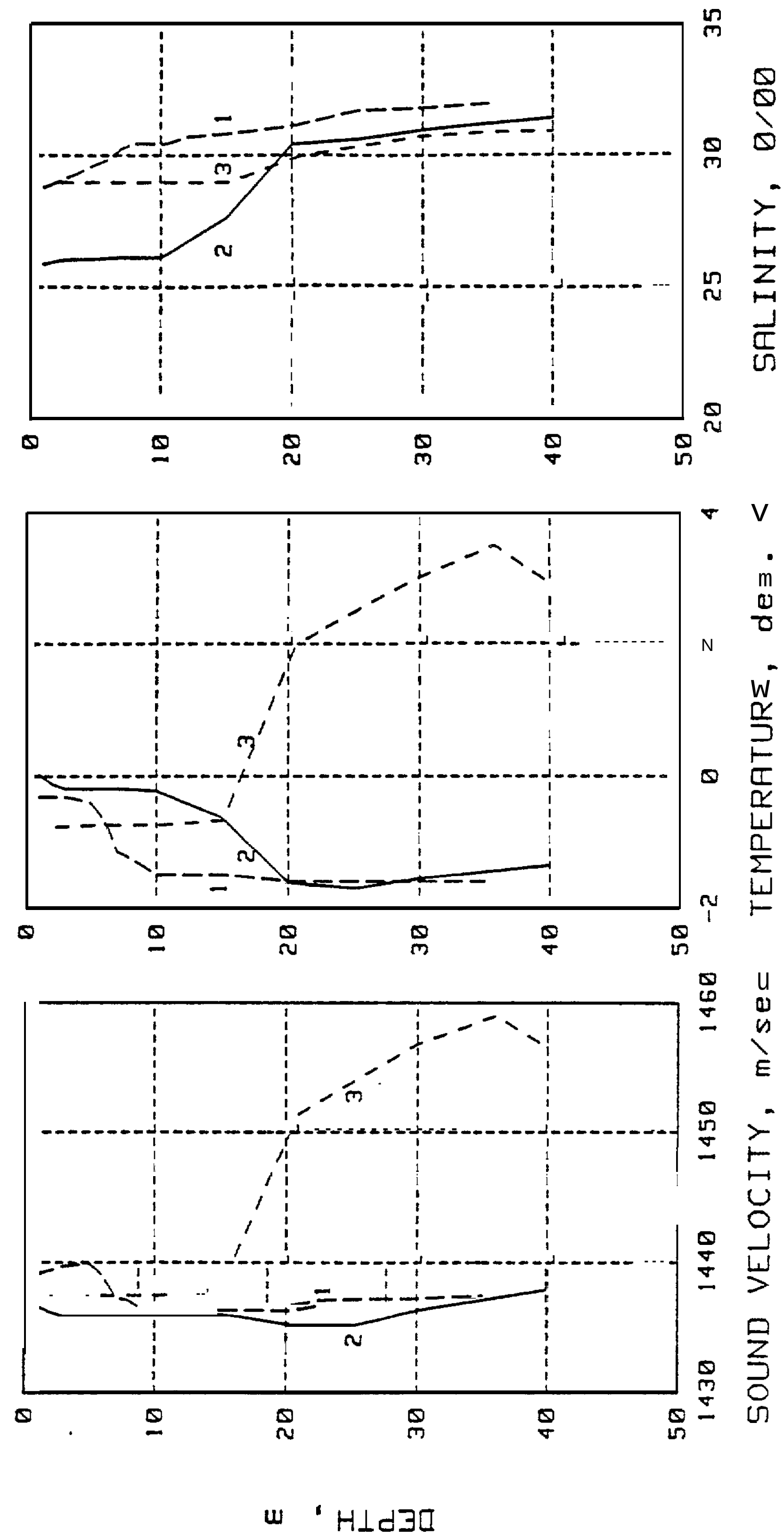


FIG. 37. ERIK SITE, ENVIRONMENTAL DATA
1 - 9/13/85, 2 - 8/30/86, 3 - 10/12/86 (POLAR STAR).

Sound transmission measurements were made to the north of this site out to a range of 20 km. The data were analyzed using the procedure outlined previously. To estimate the expected range of TL variations due to changes in SVP conditions, the downward refraction condition observed at Belcher in 1986 was assumed to also represent a probable early September condition at Erik. The POLAR STAR observations were used to represent the surface duct condition existing in mid-October. The resulting TL characteristics for 100 Hz and 1 kHz are shown in Fig. 38 extrapolated to a range of 40 km. The expected variation in the TL characteristics at 1 kHz can be seen to be very large. The most significant effect can be seen to result from the downward-refraction condition which causes increased bottom losses.

Corona Site

The Corona site (depth 35 m) was visited only briefly during the 1985 field measurement period. No SVP or TL data were obtained at that time. During the 1986 field season the site was occupied by the EXPLORER II drillship and its support vessels. Several SVP measurements were obtained near this site in conjunction with TL measurements. Three TL measurements were made: a short range measurement using the projector source to measure the effective local anomaly (needed to determine the source level of the drillship), a long range measurement (to 15.7 km) to determine the long range TL characteristics to the north of the site, and a TL measurement to 45 km northeast of the site using a seismic survey vessel as a low frequency source-of-opportunity.

The SVP data obtained during the projector TL measurement are shown in Fig. 39. A shallow sharp downward refracting gradient (curve 2) was observed during the early-September period when the TL measurements were made. This had changed to a

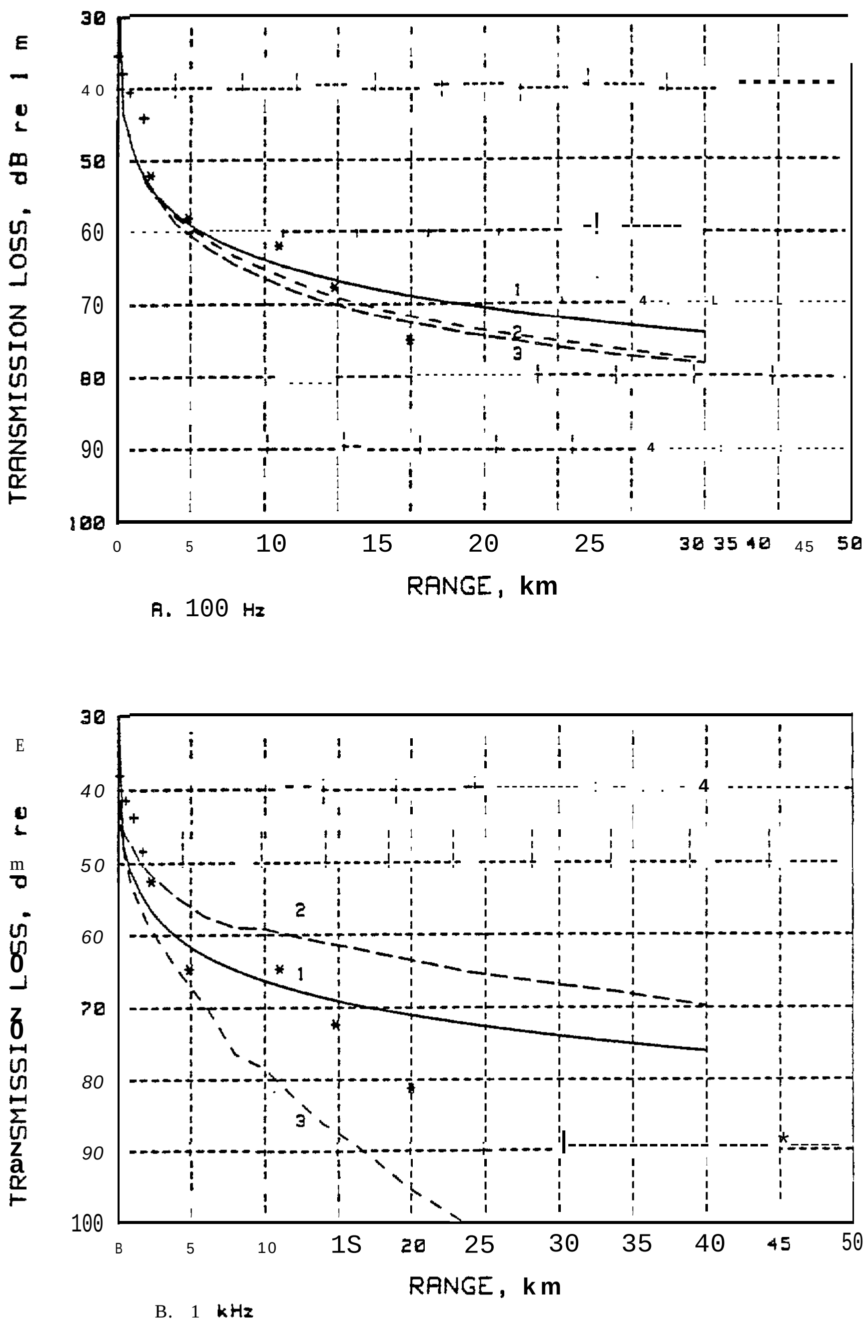


FIG. 38. ERIK SITE, NORTHWARD TRANSMISSION LOSS CHARACTERISTICS. 1 - NEUTRAL SVP, 2 - SURFACE DUCT, 3 - DOWNWARD REFRACTION. + 1985 DATA, * 1986 DATA.

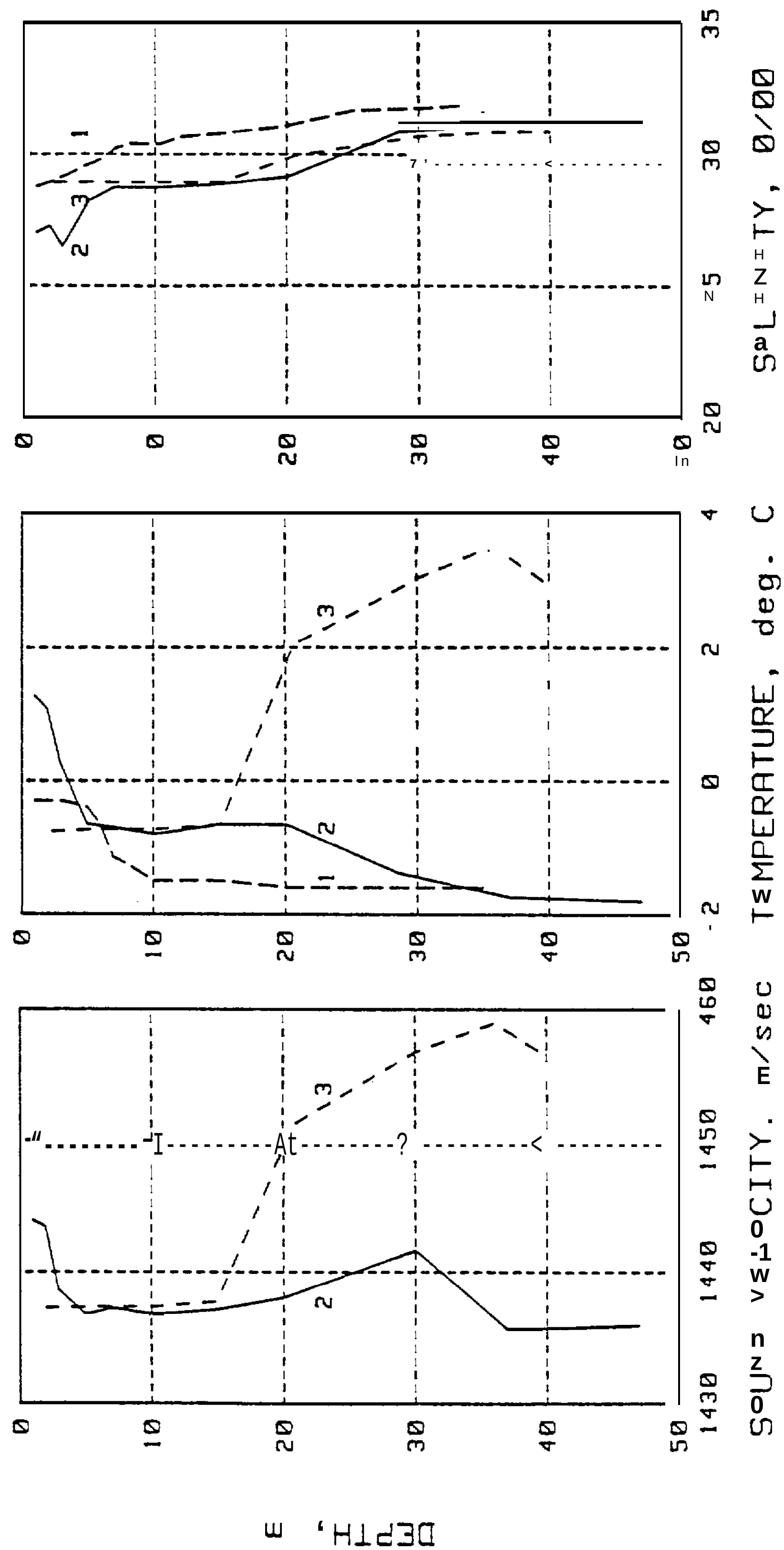


FIG. 39. CORONA SITE, ENVIRONMENTAL DATA
1 - 9/13/85 ERIK SITE), 2 - 9/2/86, 3 - 10/12/86 (POLAR STAR).

surface-duct condition by mid-October as shown by the POLAR STAR data (curve 3). The 1985 temperature and salinity data shown (curve 1) were obtained at the nearby Erik site and are included for comparison purposes.

The short range and long range projector data were analyzed to obtain the TL characteristics shown in Fig. 40. The downward refracting SVP condition did not cause a significant change in TL at 100 Hz. Only a small change was estimated to be caused by the surface duct condition. However, at 1 kHz a significant change in the TL characteristics is estimated to be caused by the expected variations in SVP conditions. The results of the low frequency TL measurements obtained during a seismic survey transect northeast of the Corona site are discussed at the end of this section.

Hammerhead Site

Hammerhead site (depth 28 m) was not visited during the 1985 field period because of the heavy ice cover conditions in this area. Ice was also present during the 1986 field period but it opened up enough to obtain TL data out to a range of 11.1 km to the northwest of the site. Concurrent SVP data were also obtained.

The SVP data obtained in September 1986 are shown in Fig. 41, again compared to the data obtained nearby in mid-October by the POLAR STAR. A shallow surface duct above 10 m can be seen to be combined with a downward refraction zone from 10 to 15 m in the September data. The October data again show a very strong surface duct combined with strong upward refraction.

The results of analyzing the TL data are shown for 100 Hz and 1 kHz in Fig. 42. Again the effects of the variations in the SVP conditions can be seen to occur primarily at high frequencies.

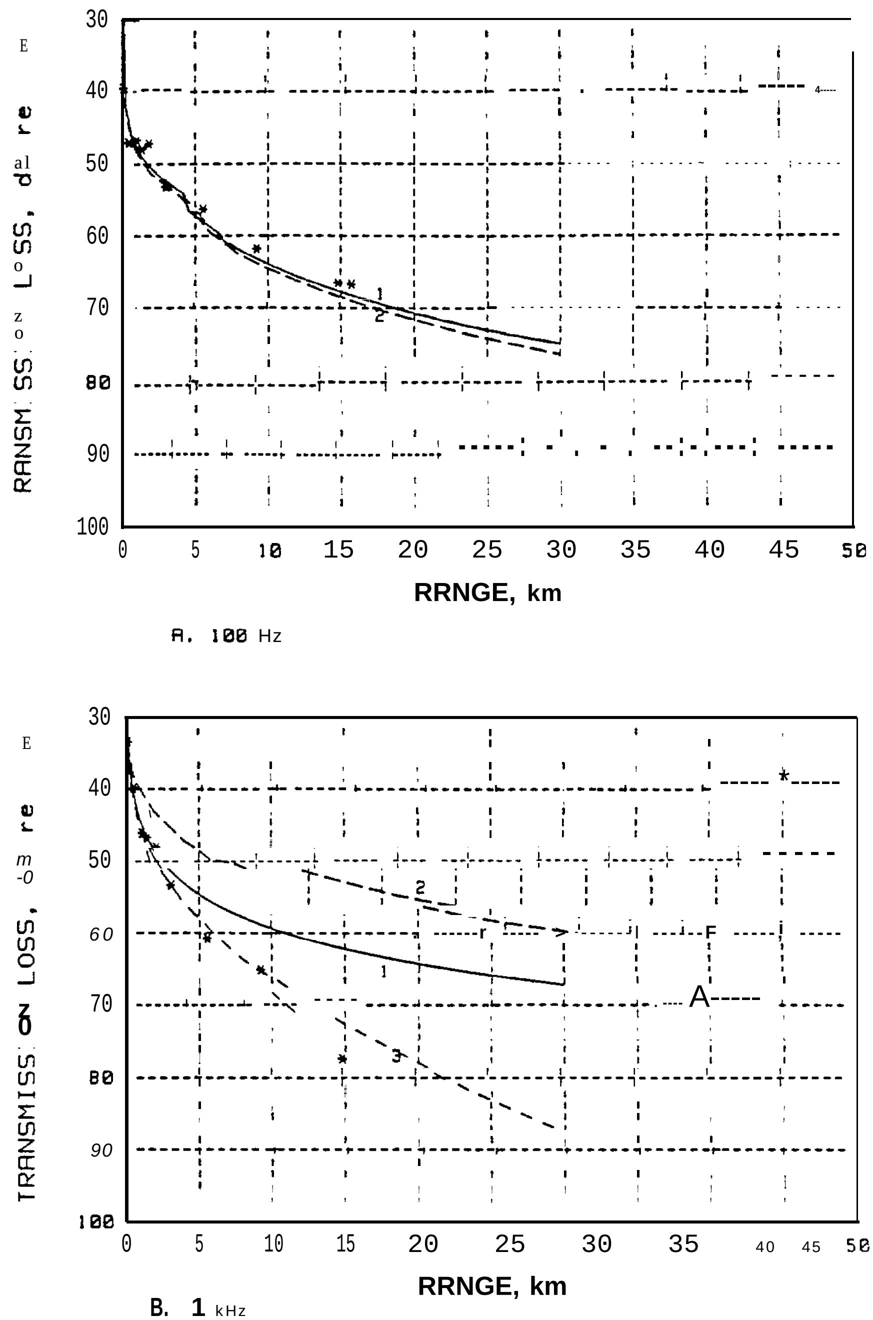


FIG. 40. CORONA SITE, NORTHWARD TRANSMISSION LOSS CHARACTERISTICS. 1 - NEUTRAL SVP, 2 - SURFACE DUCT, 3 - DOWNWARD REFRACTION. * 1986 DATA.

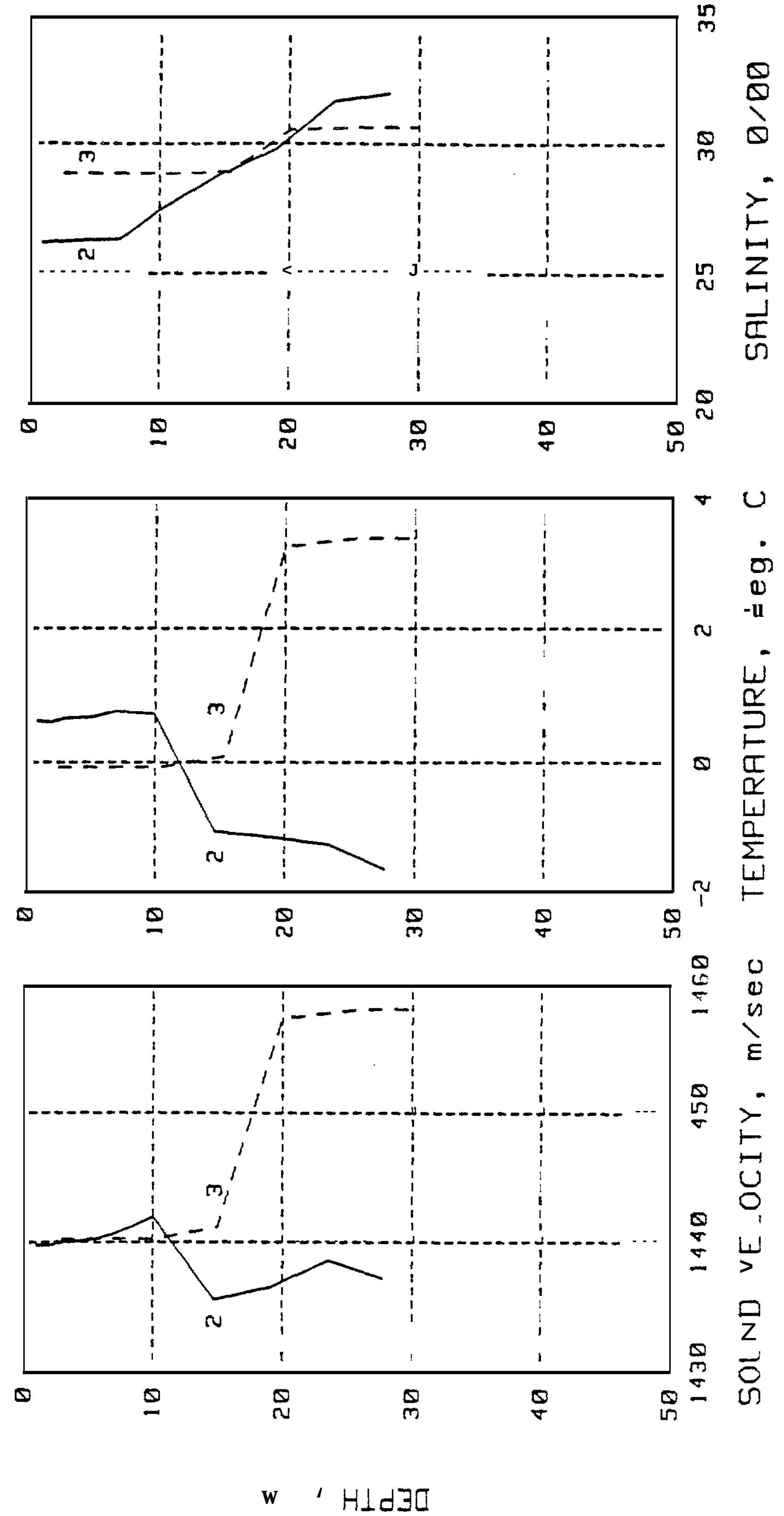


FIG. 41. HAMMERHEAD SITE, ENVIRONMENTAL DATA
(NO 1985 DATA), 2 - 9/9/86, 3 - 10/8/86 (POLAR STAR).

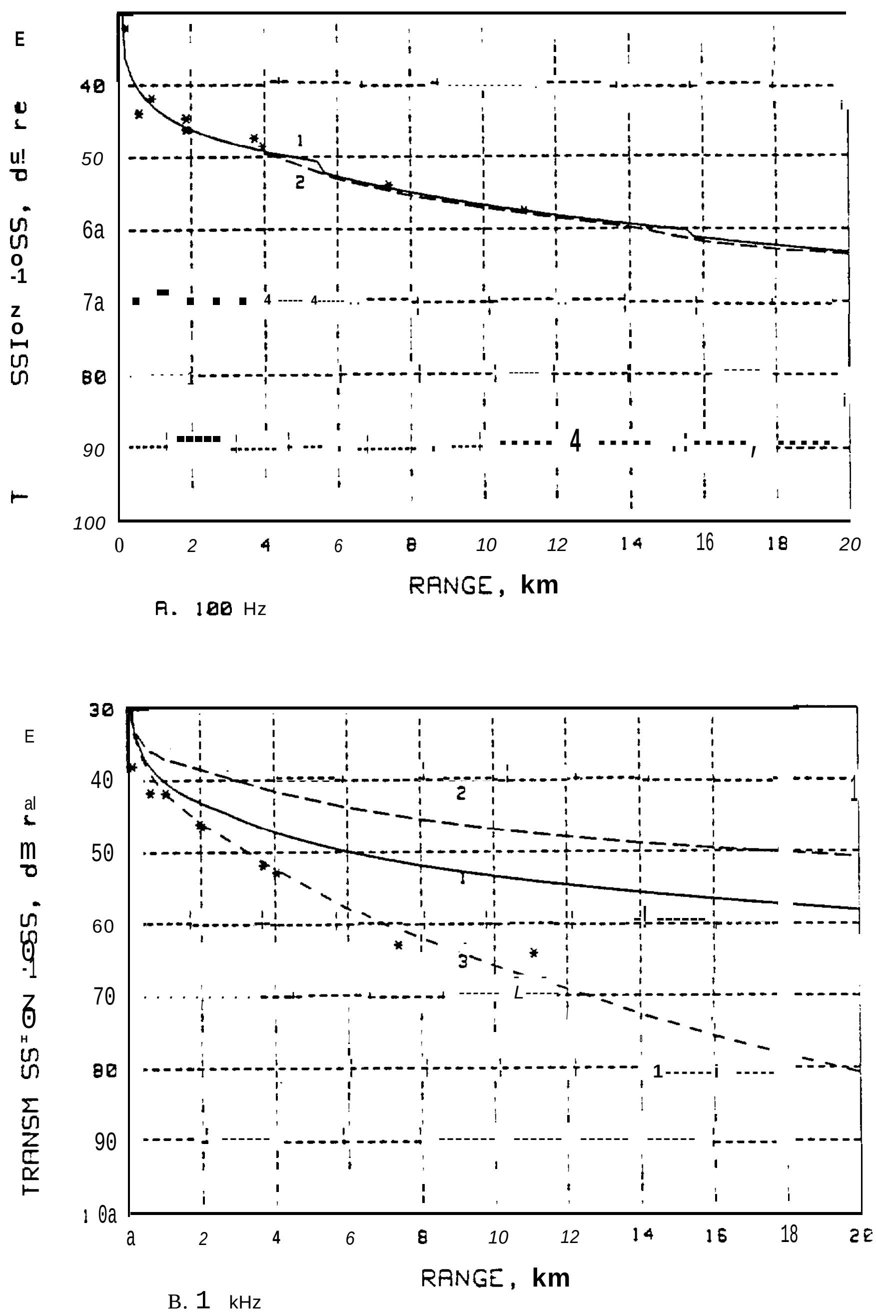


FIG. 42. HAMMERHEAD SITE, NORTHWARD TRANSMISSION LOSS CHARACTERISTICS. 1 – NEUTRAL SVP, 2 - SURFACE DUCT, 3 – DOWNWARD REFRACTION. * 1986 DATA.

Sandpiper Site

Sandpiper site was visited several times during the 1985 field season. Rig construction was underway during some of the earlier visits in that season. No activity was occurring at this site during the BBN measurement season in 1986 and the rig had been removed. The water depth (15 m) is considerably shallower at this site than at the sites to the east. The short range TL measurements made to the east of the site in 1985 showed very low values of TL which were inconsistent with a sand and silt bottom. The possible presence of a permafrost layer in the bottom was considered to be the cause of the good sound transmission conditions (see Section 2.1.1). The TL measurements in 1986 were made to the north of the site extending out to a range of 11.1 km. Concurrent measurements of SVP data were also made. Ice conditions at the site were light with only a few large blocks present.

The SVP data are shown in Fig. 43. There was a considerable amount of ice cover during the 1985 visits to the site. This may have contributed to the observed low salinity layer near the surface and the surface duct condition (curve 1) observed in the September measurement period. In September of 1986 (curve 2) the SVP conditions were slightly downward refracting. The POLAR STAR data for this area again show a surface duct condition in October which extends very nearly to the bottom. (While the POLAR STAR did not have a transect at Sandpiper, one near Prudhoe Bay starting in a water depth of 27 m and one near Harrison Bay starting in 41 m deep water demonstrate the presence of the surface duct.) It is unlikely that the previously noted subsurface intrusion of warm Bering Sea water would extend as far inshore from the shelf edge and upslope to reach Sandpiper and Orion (Fissel et al. 1987). The surface duct at Sandpiper may have been caused only by surface cooling prior to freeze-up.

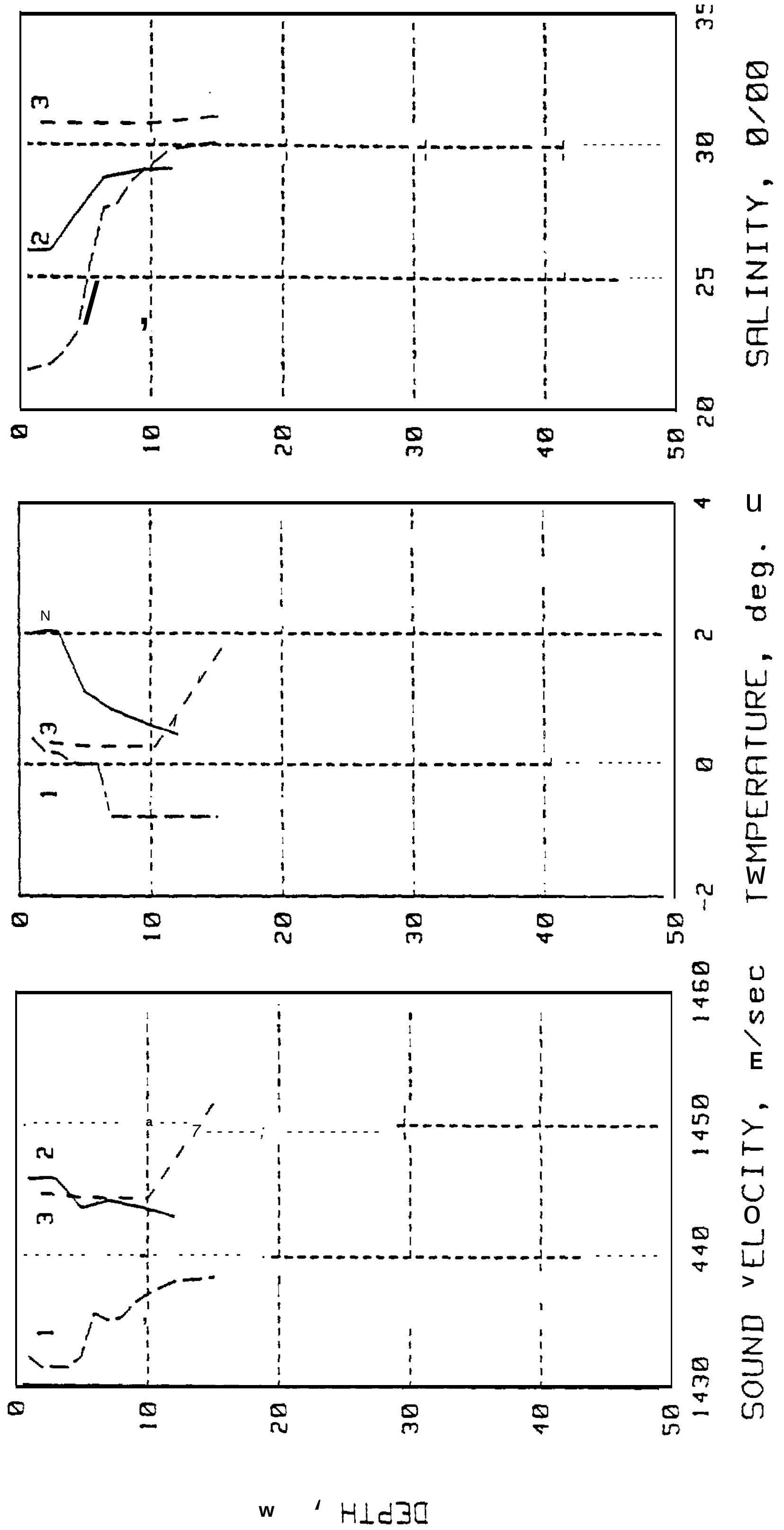


FIG. 43. SANDPIPER SITE, ENVIRONMENTAL DATA.
1 - 8/27/85, 2 - 9/1 /86, 3 - 10/16/86 (POLAR STAR).

Analysis of the 1986 TL data showed that sound propagation beyond 4 km to the north of the site had considerably higher loss than the short range propagation near the site. The spread between the TL data observed in 1985 and that observed in 1986 was greater that that expected from the SVP variations alone, as shown in Fig. 44. A compromise TL characteristic has been developed which has the correct slope to match the long range data but has a higher local anomaly value to better match the short range measurements.

Orion Site

Orion site (depth 14 m) was not visited during the 1986 field season. The results presented for this site are based on measurements made in 1985, supplemented by using the Sandpiper long range TL data since the water depth and expected bottom composition are similar at these two sites. The SVP data shown in Fig. 45 indicated that weak upward refracting conditions existed mainly as a result of lower salinity near the surface. No POLAR STAR data were available for this area, but it is probable that the surface duct condition which occurred in mid-October at the other sites would also be found at Orion. As a result the estimated variation in TL caused by SVP changes at Sandpiper was also applied to the TL characteristic for the Orion site.

The TL data obtained at this site in 1985 were limited to a range of 4.8 km with low values of TL being observed. The data obtained at longer ranges at Sandpiper showed that extrapolation of the short range data to longer ranges could cause under-estimation of the TL. Thus the TL characteristics estimated for Orion (Fig. 46) have been adjusted to have a greater loss at long range than the best-fit curve for the 1985 data would provide.

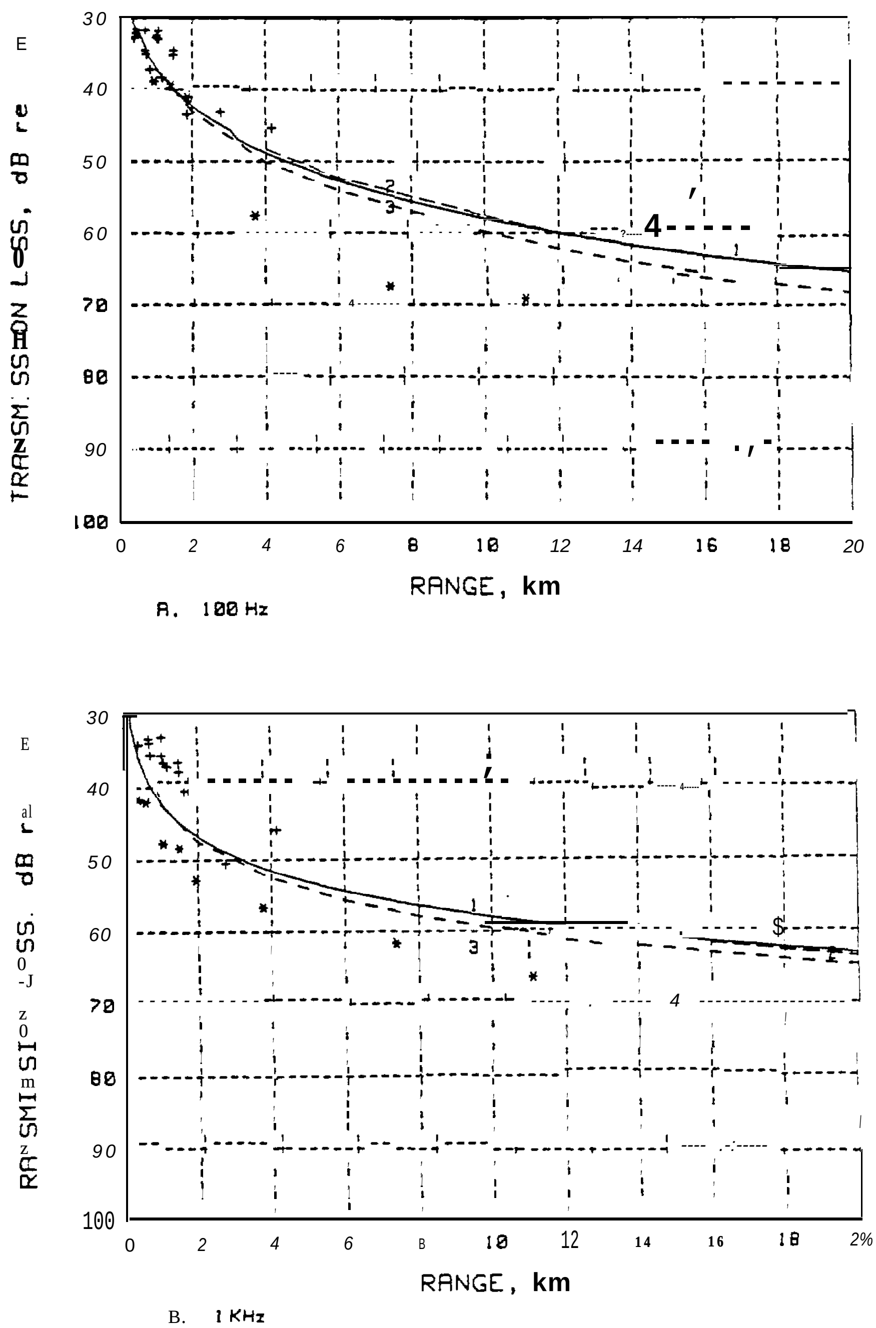


FIG. 44. SANDPIPER SITE, NORTHWARD TRANSMISSION LOSS CHARACTERISTICS. 1 - NEUTRAL SVP, 2 - SURFACE DUCT, 3 - DOWNWARD REFRACTION. + 1985 DATA, * 1986 DATA.

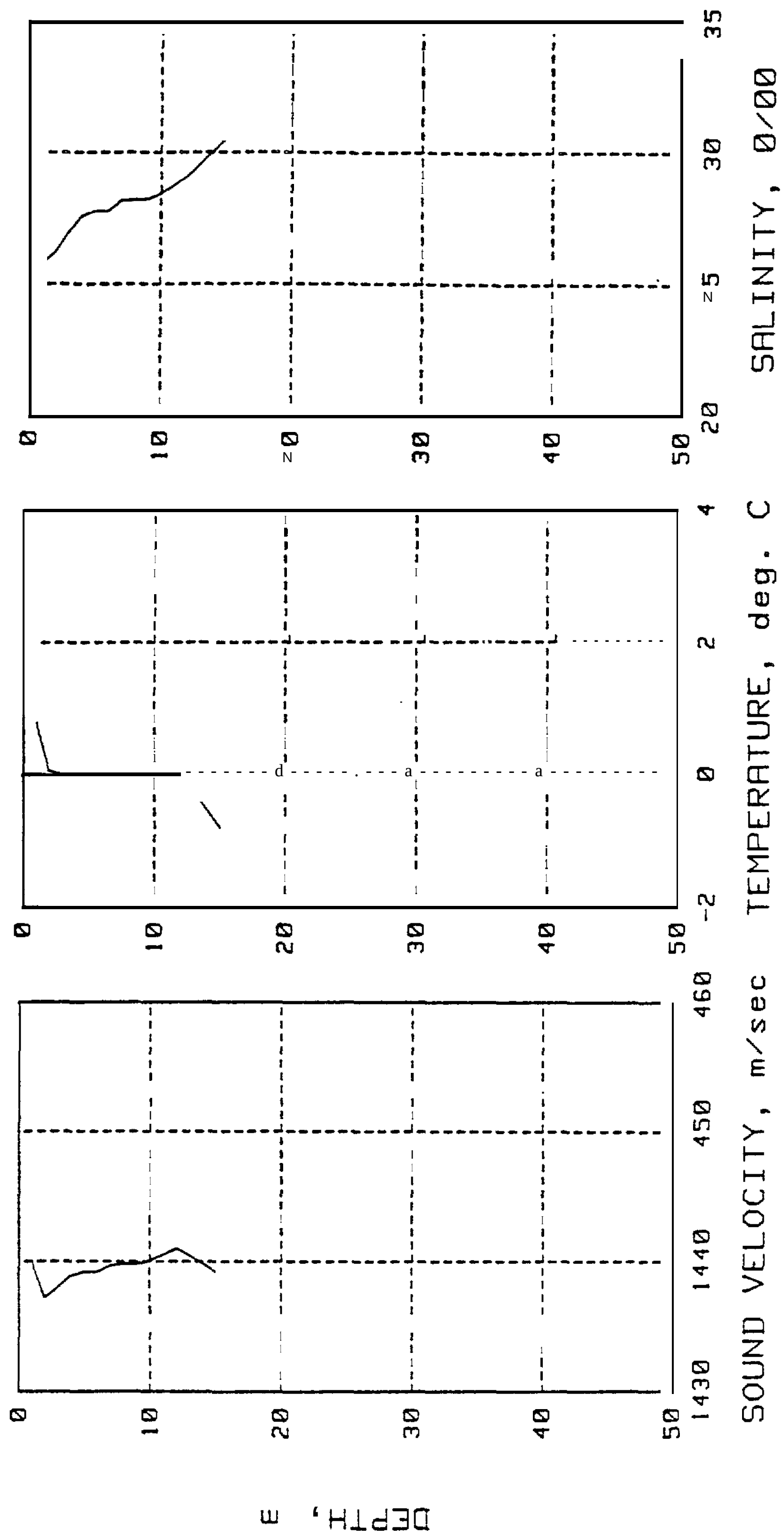
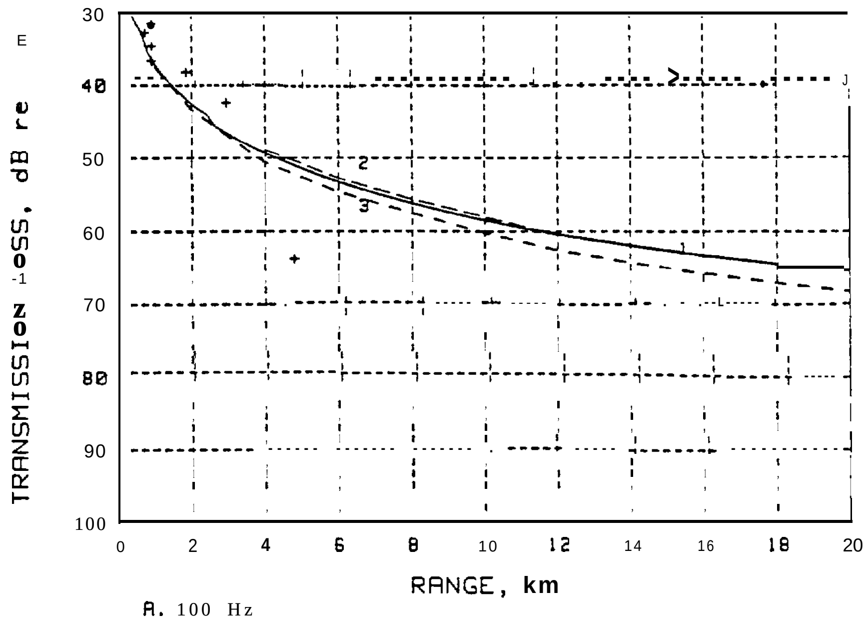


FIG. 45. ORION SITE, ENVIRONMENTAL DATA, 8/28/85.



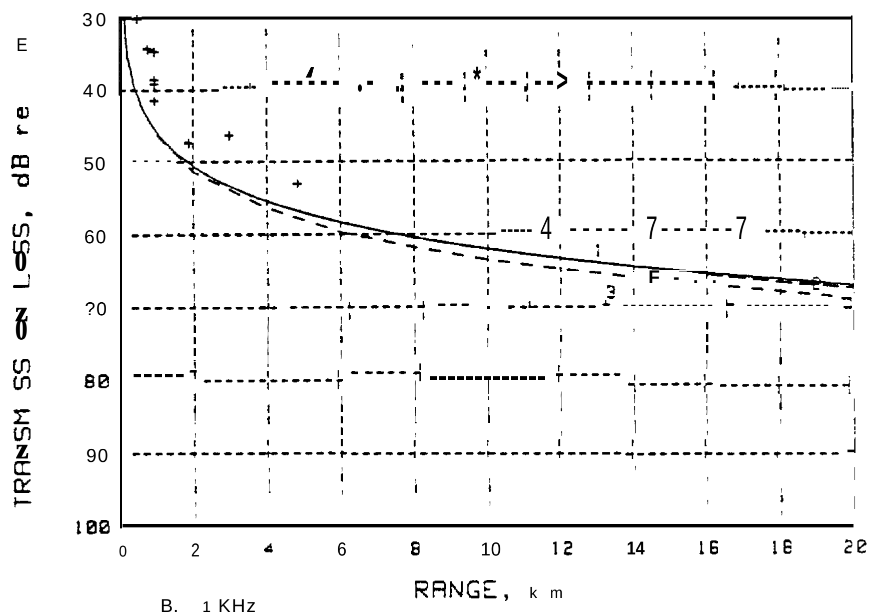
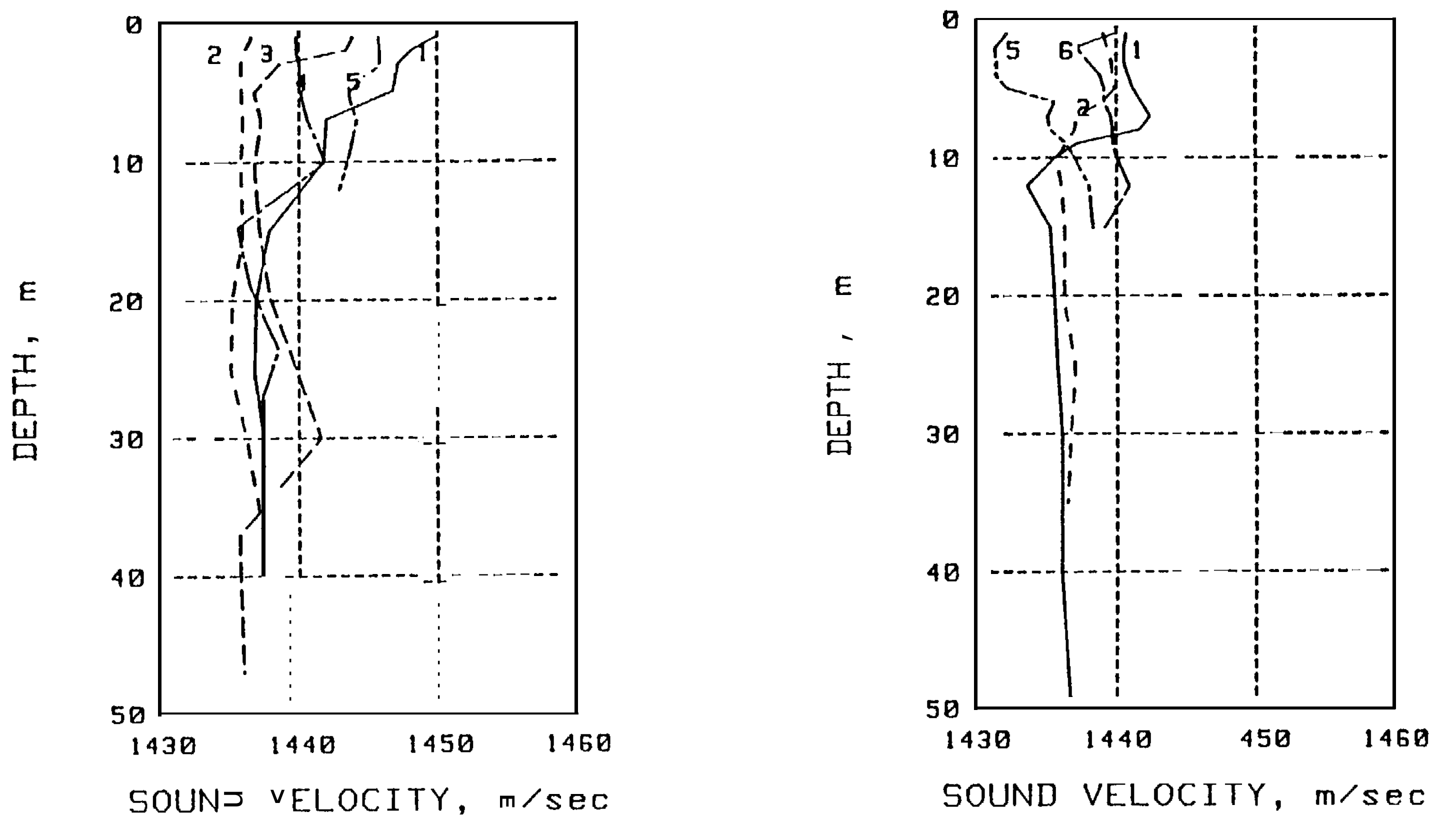


FIG. 46. ORION SITE, NORTHWARD TRANSMISSION LOSS CHARACTERISTICS. 1 - NEUTRAL SVP, 2 - SURFACE DUCT, 3 - DOWNWARD REFRACTION. + 1985 DATA.

Summary

The SVP data and the TL data for all the sites have been summarized to present an overall view of the range of values obtained for all of the measurements. Figure 47 presents a summary of the SVP data from both 1986 and 1985 field periods. These data were obtained during the period from late August to mid-September in both years. The 1986 data show a range from the strong downward refraction at Belcher to the nearly neutral profile at Erik. The 1985 data do not have as large a spread in sound velocity values but upward refracting conditions were sometimes encountered. The expected range of SVP conditions at all sites during the whale migration period can therefore be expected to vary widely, going from downward refracting in early September through a nearly neutral condition, probably by late September, to an upward refracting surface duct condition by mid-October to freeze-up. It appears that the intrusion of warm Bering Sea water near the shelf edge in 1986 (Fissel et al. 1987) has some influence on the surface duct, at least for the deep water sites with duct enhancement due to surface cooling as freeze-up approached. The presence of a late season surface duct near the shallow sites, on the other hand, indicate that the approach of freeze-up with the attendant cooling of the surface water plays an important part in establishing that duct.

The 100 Hz and 1 kHz TL characteristics for neutral SVP conditions at five sites are summarized in Fig. 48. The expected range of variation for each TL characteristic has been omitted for clarity. Note that the range of variation at 100 Hz is less than 10 dB for all of the sites. This is surprising in view of the wide range of water depths at the different sites. A wider range of variation in the TL characteristics can be seen at 1 kHz, but it remains less than 14 dB. Thus the site-to-site variation in TL at 1 kHz is less than the variation caused by changes in the SVP



A. 986 DATA

B. 985 DATA

FIG. 47. SUMMARY OF SOUND VELOCITY PROFILE DATA FOR ALL SITES, LATE AUGUST-MID-SEPTEMBER 1985-86. 1 - BELCHER, 2 - ERIK, 3 - CORONA, 4 - HAMMERHEAD, 5 - SANDPIPER, 6 - ORION.

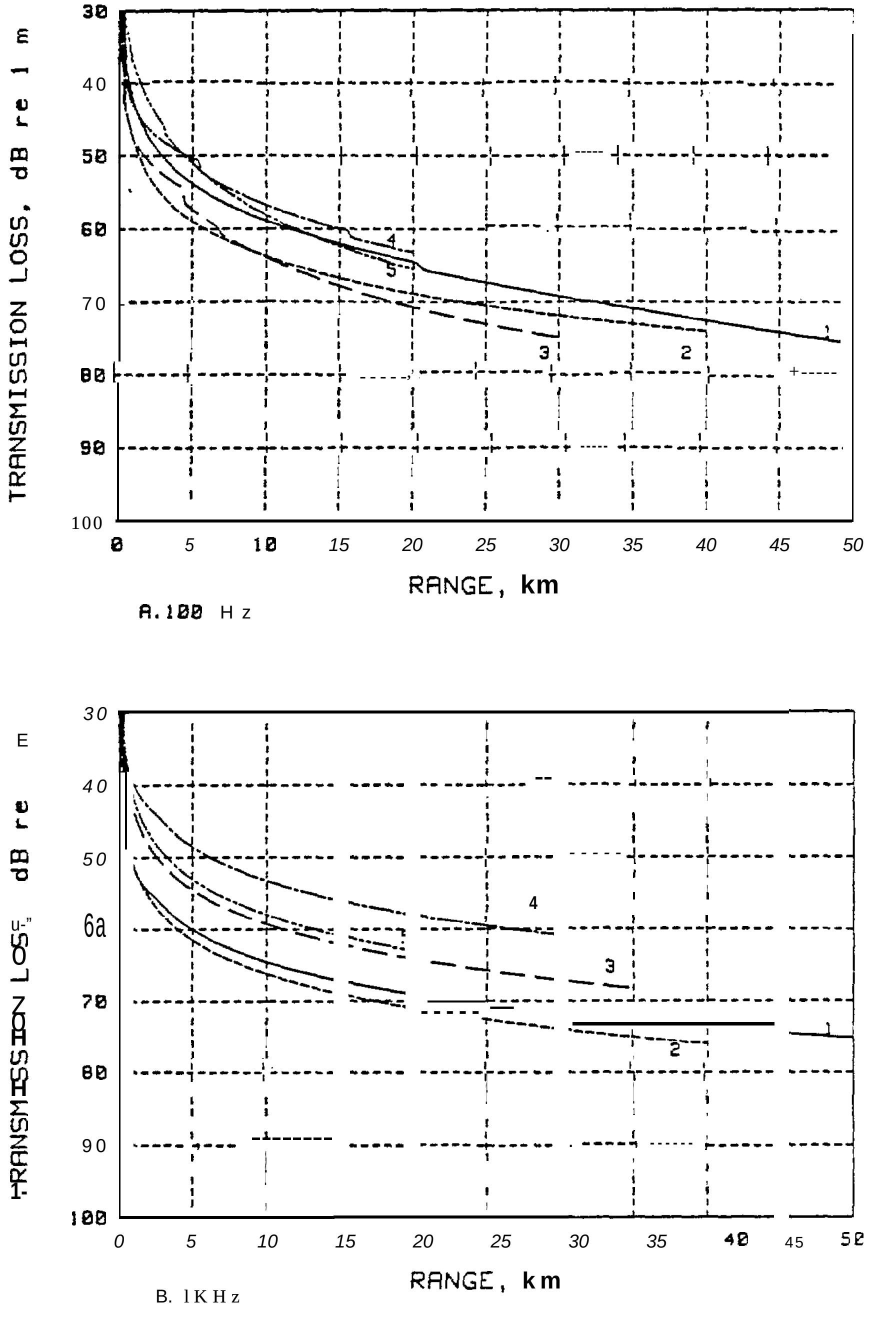


FIG. 48. SUMMARY OF TRANSMISSION LOSS CHARACTERISTICS FOR NEUTRAL SOUND VELOCITY PROFILE CONDITIONS. 1 - BELCHER, 2 - ERIK, 3 - CORONA, 4 - HAMMERHEAD, 5 - SANDPIPER.

at a given site. This is not true at 100 Hz where variations in the SVP have a smaller apparent effect than changes in bottom composition for the shallow water environment of the study sites.

The site-specific bottom loss parameters derived from the TL analysis process are tabulated in Table 8. These parameters are obtained from the best-fit Weston/Smith TL characteristics matching specific data sets and can be used in the BASIC program listed in Appendix C to reproduce these characteristics.

The BASIC program includes instructions to list the ranges at which spreading loss slope transitions occur in the best-fit model resulting from the TL analysis process. This provided information on the dominant spreading loss slope for each site and frequency. The 10 log R characteristic was found to match the data over the largest range increment for most of the sites and for most of the test frequencies.

Examination of the values obtained for the bottom loss parameter “b” shows that very small values were obtained for some of the sites. Normally a sand and silt bottom would be expected to have b values of 1.5 - 2 and a basalt bottom b values of about 0.4. Sandpiper and Hammerhead sites are observed to have b values at 100 Hz of 0.05 - 0.1. At 100 Hz the b value at Belcher is 0.3, which helps to explain why the TL characteristics for the various sites do not differ more. The shallow sites have lower bottom loss than the deeper sites which helps to compensate for the larger number reflections per unit distance which occur in transmission paths at the shallower sites.

Recent studies of the physics of sound reflection from certain types of high sound velocity bottom material show that sound may penetrate the bottom and be refracted back out without undergoing much loss (Spofford et al. 1983). This type of process does not depend on the large impedance mismatch type of reflection

TABLE 8. PARAMETERS* FOR WESTON/SMITH TL MODEL BASED ON BEST-FIT OF 1986 DATA CORRECTED TO NEUTRAL SVP CONDITIONS USING THE GENERIC SONAR MULTIPATH MODEL.

BELCHER SITE (EAST TL DATA)

F-kHz	b	Sin* c	A_n-dB	R_{max}-km	ER_{rms}-dB
0.1	0.3	0.8	5	50	1.5
0.2	0.2	0.3	3	50	1.7
0.5	0.25	0.2	3	50	1.2
1.0	0.35	0.3	-2	50	1.4
2.0	0.4	0.4	0	40	1.4
4.0	0.5	0.3	-8	10	0.8

Depth - 55 m, O slope E, .0015 slope N, -.0013 slope S

NOTE : The W/S parameters obtained from the east TL run should also be used when applying the model north of the site out to a range of 16 km. The parameters obtained from the north TL run should be used for application of the model beyond 20 km north of the site. There is a rapid increase in depth and a possible change in bottom conditions in this region. A set of calculated TL characteristics for application northward of Belcher is included in Appendix C, Table 2

BELCHER SITE (NORTH TL DATA)

F-kHz	b	$\sin\phi_c$	A_n-dB	R_{max}-km	ER_{rms}-dB
0.1	0.3	0.8	-7	20-50	3.1
0.2	0.3	0.3	-3	20-50	2.5
0.5	0.3	0.2	-3	20-50	1.3
1.0	0.2	0.3	-lo	20-50	1.5
2.0	0.45	0.3	-3	20-40	1.5

Depth - 55 m, .0035 slope N

* F = frequency in kHz
b = bottom reflection loss factor
ϕ_c = critical grazing angle of a sound raypath with the bottom
An = local anomaly due to bottom and surface reflected energy
R_{max} = maximum range for extrapolation of the transmission loss (TL) prediction
ER_{rms} = error between calculated and measured sound level.

TABLE 8. (Cont.) PARAMETERS FOR WESTON/SMITH TL MODEL BASED ON BEST-FIT OF 1986 DATA CORRECTED TO NEUTRAL SVP CONDITIONS USING THE GENERIC SONAR MULTIPATH MODEL.

ERIK SITE

F-kHz	b	$\sin\phi_c$	A_n-dB	R_{max}-km	ER_{rms}-dB
0.1	0.15	0.8	-2	40	2.7
0.2	0.2	0.3	-1	40	1.4
0.5	0.4	0.3	-1	40	2.8
1.0	0.55	0.3	-3	40	5.1
2.0	0.55	0.3	-1	40	3.9
4.0	0.6	0.3	-5	20	1.5

Depth - 40 m, O slope E, .0011 slope N, -.0015 slope S

CORONA SITE

F-kHz	b	$\sin\phi_c$	A_n-dB	R_{max}-km	ER_{rms}-dB
0.04	0.15	0.3	0 (est)	20	(from seismic array data
0.1	0.3	0.2	2	30	1.8
0.2	0.45	0.3	1	30	1.1
0.5	0.85	0.8	5	30	1.4
1.0	0.95	0.8	5	30	2.1
2.0	0.95	0.8	15	20	1.6
4.0	1.05	0.8	9	20	3.0

Depth - 35 m, O slope E, .001 slope N, -.001 slope S

HAMMERHEAD SITE

F-kHz	b	$\sin\phi_c$	A_n-dB	R_{max}-km	ER_{rms}-dB
0.1	.09	0.3	4	20	1.9
0.2	.08	0.3	-1	20	2.2
0.5	0.14	0.3	3	20	2.0
1.0	0.2	0.3	7	20	2.1
2.0	0.8	0.8	16	15	4.0
4.0	1.2	0.8	14	10	0.5

Depth - 30 m, O slope E, .0005 slope N

TABLE 8. (Cont.) PARAMETERS FOR WESTON/SMITH TL MODEL BASED ON BEST-FIT OF 1986 DATA CORRECTED TO NEUTRAL SVP CONDITIONS USING THE GENERIC SONAR MULTIPATH MODEL.

SANDPIPER SITE

F-kHz	b	$Sin\phi_c$	A_n-dB	R_{max}-km	ER_{rms}-dB
0.1	.05	0.8	5	20	7.8
0.2	0.15	0.8	5	20	2.0
0.5	0.25	0.8	4	20	1.1
1.0	0.35	0.8	3	20	l.0
2.0	0.5	0.8	10	20	3.1
4.0	0.5	0.8	4	15	4.2

Depth - 15 m, O slope E, .0008 slope N

ORION SITE (Based on Sandpiper 86 and Orion 85 data)

F-kHz	b	$Sin\phi_c$	A_n-dB	R_{max}-km
0.1	.05	0.8	5	20
0.2	0.15	0.8	8	20
0.5	0.2	0.8	4	20
1.0	0.5	0.8	0	20
2.0	1.2	0.8	6	20
4.0	1.2	0.8	2	15

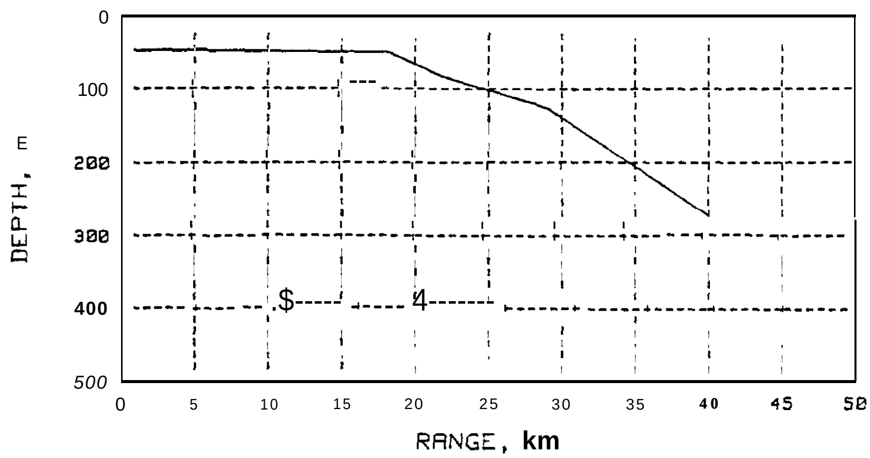
Depth - 14 m, O slope E, .001 slope N

process that occurs with a rocky bottom. It is possible that permafrost or overconsolidated clay layers which are known to exist in the study area may have this type of low-loss bottom reflectivity.

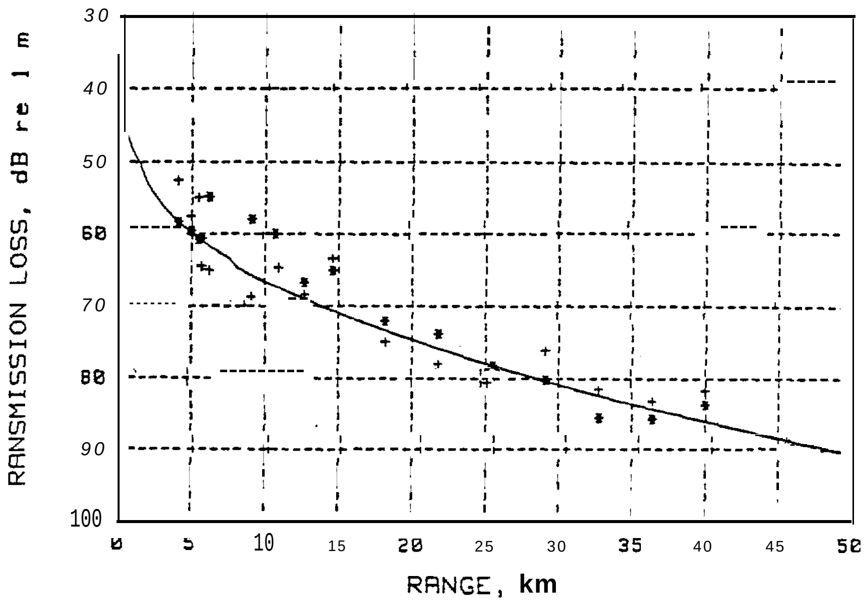
Transmission Loss Measurements Using Seismic Array Data

The high intensity energy output from a seismic array is a useful source for TL measurements. However, the usefulness of this type of source is limited to geometries where the aspect angle of the array does not change during the TL data run. The arrangement of the individual sources within the array causes its output to be directional, having the maximum peak pressure directed downward, but secondary pressure peaks are also formed. A horizontally directed secondary pressure peak is usually formed at right angles with the array axis (broadside) and a lower pressure secondary peak in line with the array axis (end-fire). Thus to insure that the effective source level of an array remains constant during a TL run, it is necessary to place the receiving position on the array track.

With the cooperation of the operator, Western Geophysical, we were able to use the output of the array on the WESTERN POLARIS as a source for a TL measurement north of Corona. The array had a firing gun volume of 1750 cu. in. The sound impulses from this array were measured as the WESTERN POLARIS proceeded on a track extending about 45 km to the northwest of Corona. The water depth along this track ranged from 46 m near the receiving location to 275 m at the termination of the run as given by the profile in Fig. 49A; with the continental shelf edge shown at about 20 km northwest of Corona. The data were subsequently analyzed to obtain the overall peak pressure and the peak pressure in 1/3 octave bands (center frequencies 40 Hz - 315 Hz) versus range from the source. The best-fit Weston/Smith characteristics were



A. DEPTH PROFILE OF SEISMIC SOURCE TRANSECT



B. PEAK PRESSURE (+), AND 100 HZ 1/3 OCTAVE BAND (*) DATA

FIG. 49. RESULTS OF TRANSMISSION LOSS ANALYSIS USING SEISMIC AIR GUN ARRAY ACOUSTIC IMPULSES [DEPTH PROFILE AND 100 HZ DATA).

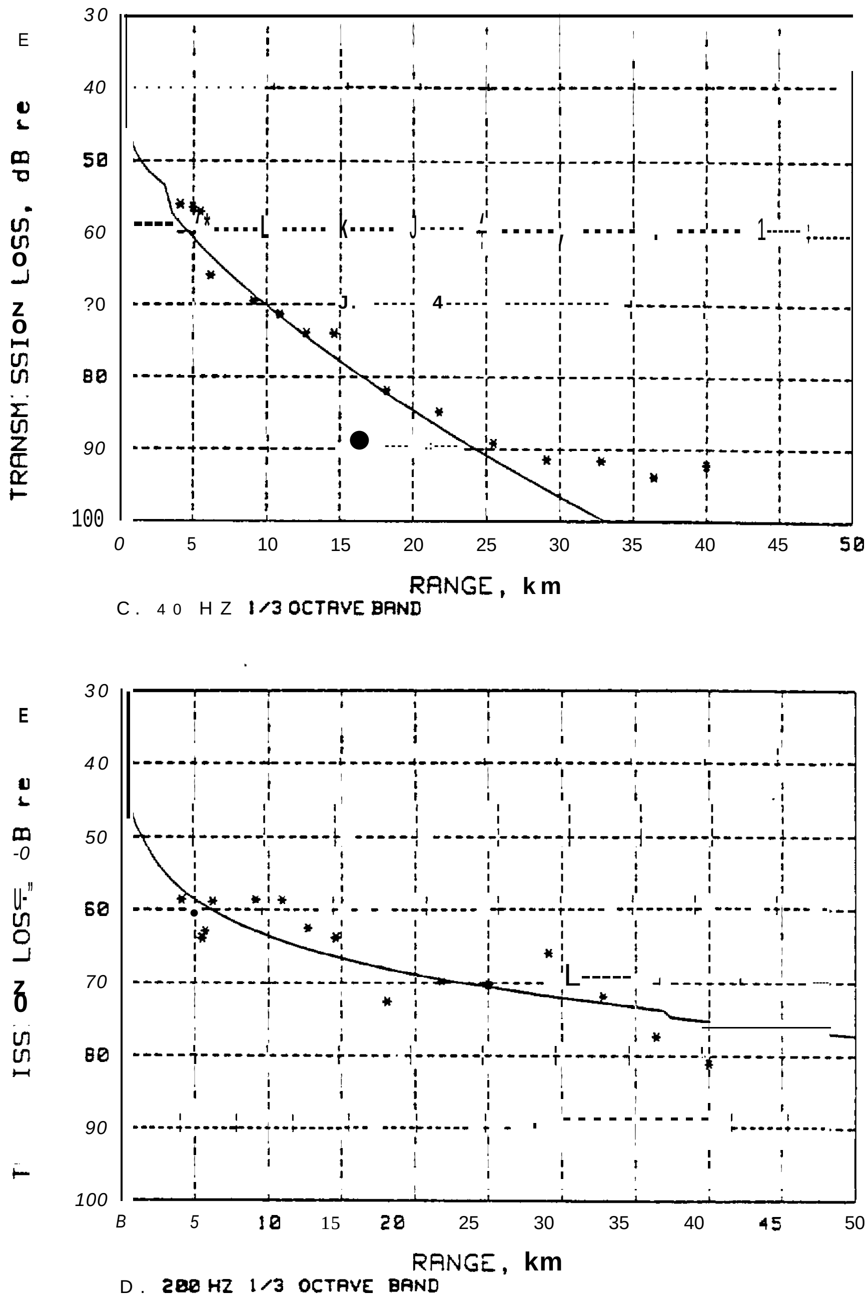


FIG. 49. (CONT.) RESULTS OF TRANSMISSION LOSS ANALYSIS USING SEISMIC AIR GUN ARRAY ACOUSTIC IMPULSES (DEPTH PROFILE AND 100 HZ DATA).

then determined for these data sets using the method of least-squares. Representative results of this analysis are shown in Figs. 49B through 49D.

A TL characteristic derived from the measurements of the overall peak pressure and of peak pressure in the 100 Hz l/3-octave band is shown in Fig. 49B. The peak pressure and the 100 Hz band data were found to have similar TL characteristics since the dominant part of the array output spectrum occurs near this frequency. Note that the effective overall (broadband) peak source level is 228 dB re 1 uPa at 1 m. This is an endfire source level. Based on the array geometry, the broadside source level is estimated to be 229 dB.

The results of the analysis of the peak pressure data in the 40 Hz l/3-octave band from the WESTERN POLARIS transect are shown in Fig. 49C. The best-fit Weston/Smith TL characteristic for the shallow part of the run can be seen to have a steeper slope than the characteristic for the 100 Hz band, but as the source moved into deeper water (see Fig. 49A) data show a decrease in the attenuation rate because of the diminished influence of the bottom. The data obtained for the 200 Hz l/3-octave band show more scatter than at lower frequencies (Fig. 49D) but the best-fit Weston/Smith TL characteristic is comparable to that obtained near Corona using the projector source.

Table 9 contains a limited comparison of the bottom parameters obtained by analyzing the array output data with bottom parameters obtained at the Corona site using the projector. The values of b obtained from the array data can be seen to agree well with those obtained using the projector. The value of b = 0.15 obtained at 40 Hz suggests that a highly reflective bottom layer exists at least out to the 25 km receiving range.

TABLE 9. PARAMETERS FOR WESTON/SMITH TL MODEL BASED ON BEST-FIT TO SEISMIC ARRAY SIGNAL DATA RECEIVED 16 KM NORTH OF CORONA SITE. (1)

F-kHz	b	$Sin\phi_c$	A_n-dB (4)	Ls '-dB	ER_{rms}-dB
.04	0.15	0.3	0	200	8.1
.10	0.40	0.3	0	209	5.2
.20	0.40	0.3	0	201	3.6
L_r(2)	0.40	0.3	0	228	4.7

PARAMETERS MEASURED NEAR CORONA SITE (FROM TABLE 5) (3)

F-kHz	b	$Sin\phi_c$	A_n-dB	ER_{rms}-dB
.10	0.3	0.2	2	1.8
*20	0.45	0.3	1	1.1

Key:

1. Peak level in l/3-octave band noted
2. Peak overall (broadband) signal level
3. Mean rms level in l/3-octave band
4. Local anomaly assumed to be zero. A calibrated sound source was not used over the seismic array track.

Comparison of Sound Propagation Conditions in Alaskan and Canadian Beaufort Sea Areas

A brief analysis was performed on data obtained by Greeneridge Sciences from several sound transmission measurements near petroleum industry sites in the eastern Canadian Beaufort Sea (Greene 1985). The locations of these sites are shown in "Fig. 50. The analysis was performed to determine if any significant differences in sound transmission conditions existed between the sites investigated in this study and similar Alaskan sites in the eastern Beaufort. Data reported for the dominant l/3-octave band for each source were analyzed by the method of least-squares to determine the parameters for the best-fit Weston/Smith TL characteristic.

The results of this analysis are shown in Table 10A. Table 10B shows the parameter values obtained from the TL measurements at the Alaskan Beaufort study sites (the low frequency results reported previously in Table 8 are repeated here for convenience). The lowest bottom loss condition in the Canadian Beaufort, b = 0.05 at a frequency of 80 Hz, is similar to the values obtained at 100 Hz for the Hammerhead, Sandpiper and Orion sites. Intermediate values of b = 0.2 to b = 0.4 were observed in both areas in the 200 - 500 Hz frequency range; however the values of b = 0.9 to b = 1.15 observed for 250 Hz at the EXPLORER II and AQUARIUS dredge sites in the eastern Beaufort are higher than the highest estimated value of b = 0.45 observed for 200 Hz at the Corona site in the western Beaufort. The two sites in the eastern Beaufort were separated by about 50 km and had different water depths. More data are needed to determine whether or not the higher bottom loss values observed for 200 to 250 Hz are site specific or are representative of a large region. The lower values of b observed for frequencies above 250 Hz at other sites in the eastern Beaufort Sea suggest that this is not a large regional effect since the parameter b is normally expected to

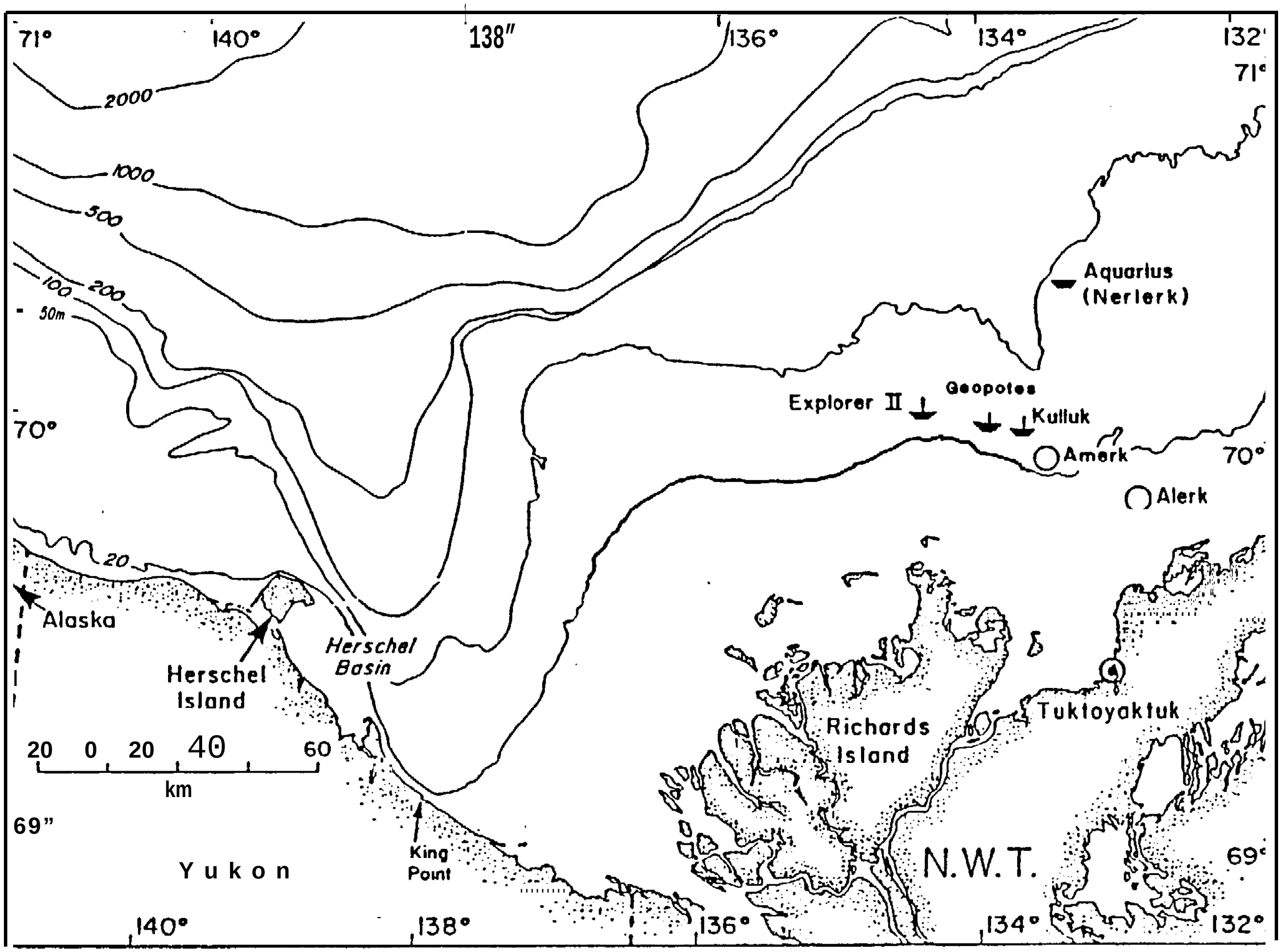


FIG. 50. LOCATIONS OF SELECTED INDUSTRIAL SITES IN EASTERN (CANADIAN) BEAUFORT SEA WHERE ACOUSTIC DATA WERE OBTAINED (FROM GREENE 1985).

TABLE 10. COMPARISON OF SOUND TRANSMISSION CHARACTERISTICS OF PETROLEUM INDUSTRY SITES IN THE EASTERN (CANADIAN) AND WESTERN (ALASKAN) BEAUFORT SEA BASED ON TRANSMISSION LOSS MODEL PARAMETERS.

A. EASTERN BEAUFORT DATA OBTAINED BY GREENERIDGE SCIENCES (APPENDIX B IN MILES ET AL. 1986)

Source	Date	Water Depth	Freq. Band-Hz	b	$\sin\phi_c$	L_s-dB	ER_{rms}-dB	Ref. Fig.
Dredge GEOPOTES (Underway)	8/05/81	25 m	80	0.05	0.8	180	1.5	B18
Dredge AQUARIUS	8/12/83	46	250	1.15	0.3	175	1.8	B12
EXPLORER II	8/06/81	27	250	0.90	0.3	169	1.5	B6
Caisson Island (Amerk)	8/29/84	28	315	0.20	0.3	162	2.1	B10
Dredge BEAVER MACKENZIE	8/06/81	13	400	0.25	0.3	161	1.2	B14
Conical Drilling Unit (KULLUK)	8/29/84	31	630	0.40	0.3	173	2.7	B8

B. WESTERN BEAUFORT DATA REPORTED IN TABLE 5, USING PROJECTOR SOURCE

Site	Water Depth	Freq. Band	b	$\sin\phi_c$
Belcher	55 m	100	0.3	0.8
		200	0.2	0.3
		500	0.25	0.2
Erik	40 m	100	0.15	0.8
		200	0.2	0.3
		500	0.4	0.3
Corona	35 m	100	0.3	0.2
		200	0.45	0.3
		500	0.85	0.8

Site	Water Depth	Freq. Band	b	$\sin\phi_c$
Hammerhead	30 m	100	.09	0.3
		200	.08	0.3
		500	0.14	0.3
Sandpiper	15 In	100	.05	0.8
		200	0.15	0.8
		500	0.25	0.8
Orion	14 m	100	.05	0.8
		200	0.15	0.8
		500	0.2	0.8

remain constant or increase with frequency. Hence, the sound propagation characteristics of the two regions of the Beaufort Sea seem similar based on the limited data available at the present time.

Comparison of Sound Transmission Characteristics at the Western Beaufort Sites With Sites in the Bering Sea and off the California Coast

Shallow water sound propagation in the Alaskan Beaufort Sea was also compared to propagation at non-Beaufort sites using recently acquired data from air gun measurements near St. Lawrence Island and in Estero Bay, California (Malme et al. 1986a,b). In Fig. 51A the 100 Hz TL characteristic obtained at the Sandpiper site (15 m) is compared with TL characteristics obtained for similar depths near St. Lawrence Island and in Estero Bay. The Weston/Smith Model parameters for these characteristics are shown in Table 11. The probable presence of permafrost or overconsolidated clay is considered to cause the low values of the bottom loss parameter, b, at the Sandpiper site. The Bering Sea and California sites have a thin layer of sand/silt with an underlying layer of rock at an undetermined depth. The table also shows the TL parameters obtained for measurements in deeper water off the Big Sur coast (Malme et al. 1986b). The bottom loss parameters shown are representative of regions with a rough rock bottom and with deep sediment bottoms.

Since many industrial sources have significant noise output at frequencies above 100 Hz, a comparison of the TL characteristics at 250 Hz was also made. Figure 51B shows a comparison of the TL at Belcher (55 m) in the Alaskan Beaufort with the TL obtained for a similar depth at a site off Soberanes Point, California (Malme et al. 1983). The difference in TL is not as pronounced at this frequency - particularly at ranges less than 2 km.

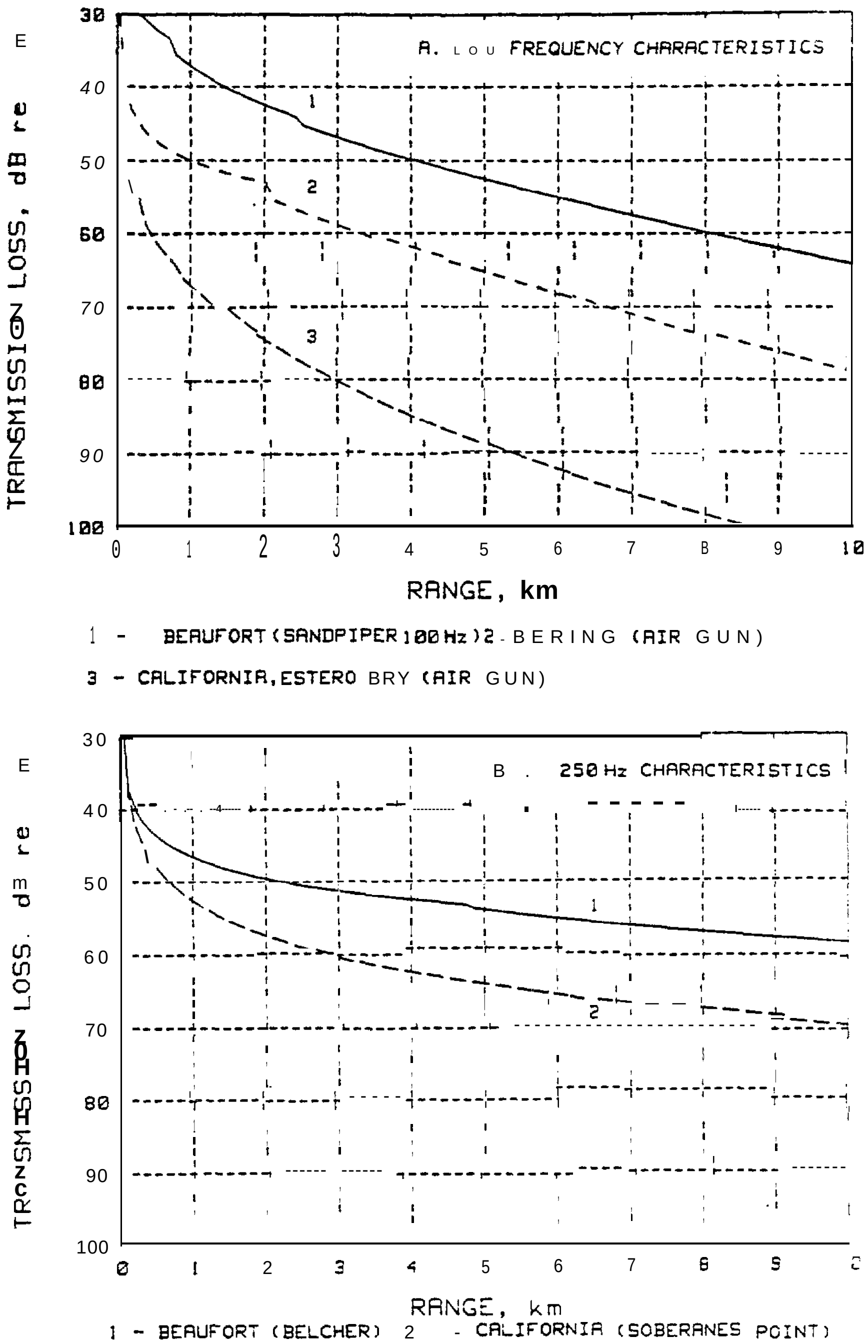


FIG. 51. COMPARISON OF TRANSMISSION LOSS CHARACTERISTICS FOR DIFFERENT **AREAS** WITH SIMILAR WATER DEPTHS.

TABLE 11. COMPARISON OF SOUND TRANSMISSION CHARACTERISTICS AT BEAUFORT SEA, BERING SEA, AND CALIFORNIA COAST TEST SITES, BASED ON TRANSMISSION LOSS MODEL PARAMETERS.

Source/Location	Water Depth	Freq. Band-Hz	b	$\sin\phi_c$	A_n-dB	ER_{rms}-dB	Reference
Projector/Sandpiper (Beaufort)	15	100	0.05	0.8	5	7.8	Table 5
Air Gun/St. Lawrence (Bering)	14	100	0.06	0.3	-6	1.4	Malme et al. 1986a
Air Gun/Estero Bay (Cal. Coast)	35	100	0.16	0.8	-8	8.4	Malme et al. 1986b
Air Gun/Soberanes pt. (Cal. Coast)	80	70	2.0	0.4	0	4.7	Malme et al. 1986b
Air Gun/Pt. Estero (Cal. Coast)	183	70	0.4	0.1	0	2.5	Malme et al. 1986b

b = bottom reflected loss factor

ϕ_c = critical grazing angle

An = local anomaly

ER_{rms} = Error between calculated and measured sound level

3.4 Zones of Influence on Whales*

3.4.1 Dominant frequency components for each industrial source

The nine industrial sources considered in the zone of influence analyses can be divided into three groups of three:

1. stationary continuous sources--a pair of tugs forcing a barge against an artificial island, drilling by a drillship, and drilling on an artificial island,
2. vessels underway--the tug ARCTIC FOX and the icebreakers CANMAR KIGORIAK and ROBERT LEMEUR underway in open water, and
3. intermittent sources--icebreaker ROBERT LEMEUR pushing ice, a barge-mounted clam-shell dredge (ARGILOPOTES), and tug ARCTIC FOX while it was towing a loaded barge.

Table 12 shows estimated source levels of the sounds from these nine sources, considering various l/3-octave bands where source levels were especially high (see Section 3.2 for details). Table 12 also shows the estimated median ambient noise levels in the corresponding l/3-octave bands (see Section 3.1 for details). Sound propagation calculations were done for each of these combinations of source level and ambient noise level.

A. Stationary sources

When two operating tugs held a barge stationary against Sandpiper Island for several hours in 1985, the estimated 1/3-octave source spectrum for this bollard condition of the tug was highest, relative to the ambient noise, around 300 Hz (163 dB), 1500 Hz (164 dB), and 4000 Hz (160 dB; Fig. 29 and Table 7). Propagation calculations were done for these three frequency/ source level combinations.

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*By W. John Richardson, LGL Ltd., environmental research associates.

Table 12. Dominant frequencies and source levels for industrial sources considered in zone of influence analyses. This table gives center frequencies of the 1/3-octave bands with maximum source level (or maximum ratio of source level to ambient level). Source levels and median ambient noise values for the corresponding l/3-octave bands are listed (see sections 3.1 and 3.2 for derivation).

Industrial Source	1 /3-OB Center Frequency (Hz)	1/3-OB Source Level (dB re 1 μPa)	1/3-OB Median Ambient Noise Level (dB re 1 μPa) Orion & Sandpiper	Hamhd, Corona Erik & Belcher
A. Stationary Sources				
2 Tugs at	300 Hz	163 dB	84 dB	84 dB
Sandpiper Isl---	1500	164	81	82
bollard	4000	160	77	81
Drillship	63	167	82	90
EXPLORER II--	160	162	84	86
drilling	315	160	84	84
Drilling on Sandpiper 1s1.	40	145	82	91
B. Vessels Underway				
Tug at Erik--	1000	164	82	82
underway *	2500	149	79	81
Icebreaker	63	173	82	90
KIGORIAK	100	173	83	88
at 10 kt	200	168	84	85
	315	166	84	84
	800	162	83	82
Icebreaker	40	169	82	91
R. LEMEUR	100	164	83	88
at 10 kt	315	163	84	84
C. Intermittent Sources				
Icebreaker	100	183	83	88
R. LEMEUR--	250	182	84	85
pushing Ice	400	180	85	83
	2000	167	80	81
	4000	174	77	81
Dredge at Erik--	250	162	84	85
raising clamshell	750	158	84	82
	1250	158	82	82
Tug at Erik--	1000	170	82	82
towing barge*	3500	164	78	81

*No data for frequencies below 400 Hz.

The drillship EXPLORER II drilling at Corona in 1986 produced high levels of sound in l/3-octave bands near 63 Hz, 160 Hz, and 315 Hz (Fig. 25; Table 7). Estimated source levels in these three bands were 167, 162, and 160 dB, respectively. These data are considered to be more reliable than the preliminary estimates of EXPLORER II source levels used by Miles et al. (1986). Thus, the results for EXPLORER II given here supersede those in the previous report.

During drilling at Sandpiper Island in 1985, the dominant sound was a tone at 40 Hz (Fig. 30; Section 3.2; see also Greene in Johnson et al. 1986). The estimated source level for this tone, and for the l/3-octave band containing it, was 145 dB. This was the only frequency/source level combination used in analyses of zones of influence around Sandpiper Island.

B. Vessels underway

When the tug ARCTIC FOX was underway near Erik in 1985, the l/3-octave band with the highest measured source level (and source level : ambient ratio) was that near 1000 Hz (Fig. 22). The source level in that band was 164 dB. The source level : ambient ratios for many higher frequency bands were similar to one another; we have used the source level of 149 dB in the band centered at 2500 Hz as an example. No data were available for frequencies below 400 Hz (Sec. 3.2). It is possible that there was a higher source level in some low frequency band than in that near 1000 Hz.

When the 16,800 bhp icebreaker CANMAR KIGORIAK was underway in open water at 10 kt in 1986, the estimated source levels were highest in absolute terms and/or relative to median ambient noise in the l/3-octave bands centered at 63, 100, 200, 315 and 800 Hz (Fig. 27 and Table 7). Source levels in these bands ranged from 173 dB down to 162 dB (Table 12).

When the 9600 bhp icebreaking supply vessel ROBERT LEMEUR was underway in open water at 10 kt in 1986, the l/3-octave bands with highest absolute or relative levels were centered at 40 Hz (169 dB), 100 Hz (164 dB), and 315 Hz (163 dB). These levels were slightly less than those for the more powerful KIGORIAK underway at similar speed (Fig. 23 vs. 27; Table 7).

c. Intermittent sources

When ROBERT LEMEUR was pushing ice in 1986, the source levels in the dominant l/3-octave bands were as high as 180-183 dB re 1 μPa in several bands (Tables 7 and 12, Fig. 26). These were the most intense continuous sounds from any industrial source studied during this project.

When the dredge bucket on ARGILOPOTES was being hauled up at Erik in 1985, strong tones were recorded at various harmonics of 125 Hz, although not at 125 Hz itself (see Fig. 23, 53 in Miles et al. 1986 and Fig. 21 and Table 7 herein). Because the sound levels of the tones are bandwidth-independent, the levels in the l/3-octave bands that contained these tones were very similar to the levels of the tones themselves. Levels at 250 Hz, 750 Hz and 1250 Hz were especially high relative to ambient noise levels. The approximate peak l/3-octave source levels at these three frequencies were 162, 158 and 158 dB re 1 μPa, respectively. Consequently, propagation calculations were done for these three frequency/source level combinations.

When the tug ARCTIC FOX was towing a fully-loaded barge away from the Erik dredge site in 1985, the l/3-octave band with the highest measured source level (170 dB) was centered at 1000 Hz (Fig. 22 and Table 7). Band levels were more or less independent of frequency from 1500 Hz to 5000 Hz. However, within this range, the band with highest level and highest signal : average ambient ratio was near 3500 Hz (164 dB). These two frequency/

source level combinations were used in propagation calculations. As noted earlier, no data were available for frequencies <400 Hz on this occasion.

3.4.2 Zones of audibility

Bowhead and gray whales are expected to be able to detect industrial sounds in the approximate range 40 or 50 Hz to 4000 Hz if the received noise level in any l/3-octave band exceeds the ambient level in the corresponding band (see Section 2.3.1). We hypothesized that each of the nine sources of industrial noise noted above was operating in turn at each of six sites. We used the site-specific Weston/Smith sound propagation models developed in Section 3.3 to predict the received levels as a function of range and bearing from these sites. The estimated ambient noise statistics from Section 3.1 (Table 12) were used to estimate the range at which the received level would equal the ambient level.

For each of the three intermittent sources, the calculations are based on the source level at times of peak noise output. The zone of aubibility would be smaller in radius at times when the source level of the noise was lower.

The diagrams in this Section show the results for the 1/3-octave band that would be detectable farthest away under median ambient noise conditions. No diagrams are shown for “tug ARCTIC FOX underway at Erik", for which the results were similar to those for “tugs in bollard condition at Sandpiper”. Data for all nine sources appear in the tables, which give the maximum ranges at which each industrial source would be audible under 5th and 95th percentile ambient noise conditions as well as median (50th percentile) conditions. Because the attenuation rate usually was different at different frequencies, the 1/3-octave band detectable farthest away under median ambient conditions was not always detectable quite as far away as some other bands under 5th or

95th percentile conditions. Thus, the tables--not the diagrams--should be used to look up the potential zone of audibility under 5th and 95th percentile conditions. Detailed results for all l/3-octave bands that were analyzed are given in Appendix D.

Orion. -- If the dredge, tugboats, or icebreakers KIGORIAK or LEMEUR operated at Orion, the industrial noise level in at least one l/3-octave band would be expected to remain above the median ambient noise level in the corresponding band out to ranges of 38 km or more to the east or west (Fig. 52; Table 13). To the north, where water depth increases with increasing range, the noise from each of these operations is predicted to be above the ambient level to ranges beyond 50 km. Thus, at least 50% of the time, a dredge, tug or icebreaker operating at Orion would be expected to be detectable at least 38 km east or west, and >50 km north. If the drillship EXPLORER II could operate in water as shallow as that at Orion, it is expected to be detectable almost as far away--30 km east or west and 50+ km north--under median ambient conditions. However, all of these distances exceed the maximum range where the Weston/Smith sound models are expected to give reasonably accurate results. In Figure 52, the estimated received levels are shown as dashed lines at ranges greater than the “maximum reliable range”.

The estimated ranges at which the received noise from these same industrial operations would exceed the 95th percentile ambient noise were 16 to 50+ km to the east or west of Orion and 23 to 50+ km to the north (Table 13). Thus, 95% of the time, sounds from a dredge, tugs, icebreaker or drillship at Orion would be potentially detectable at those distances from Orion. Some of the shorter estimates for east and west bearings were within the range where the Weston/Smith models are believed to be reasonably accurate (Table 13). Again, all estimates for northerly bearings were well beyond the maximum range where the model can be assumed to be reliable.

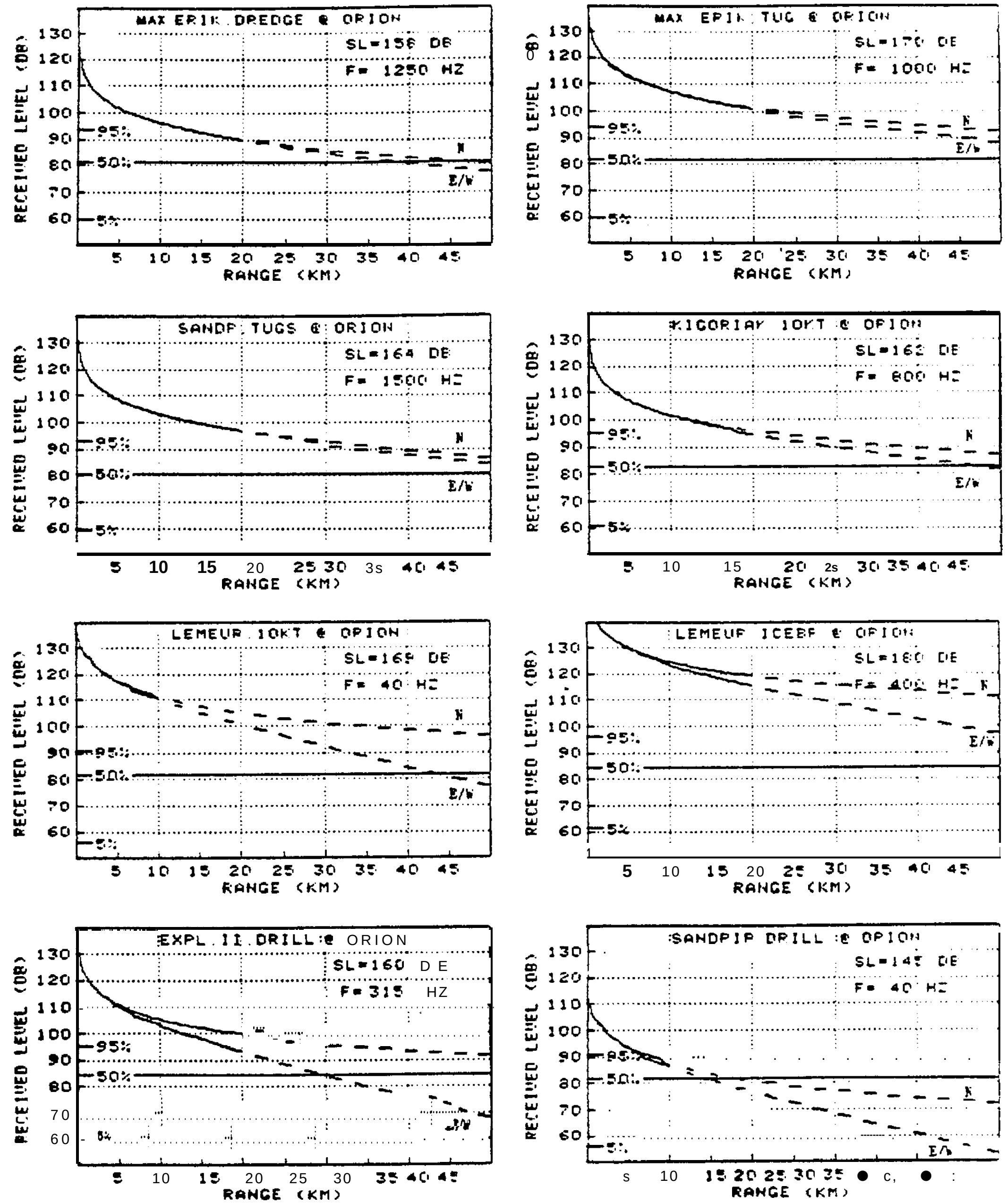


FIG. 52. ESTIMATED RECEIVED LEVELS OF **INDUSTRIAL** NOISE AT VARIOUS DISTANCES FROM THE ORION SITE IF EACH OF EIGHT **INDUSTRIAL** SOURCES WERE OPERATING THERE. ESTIMATED RECEIVED LEVELS WITH CONSTANT WATER DEPTH (WNW AND ESE OF ORION) AND FOR INCREASING WATER DEPTH (NNE OF ORION) ARE SHOWN. **IN** EACH GRAPH, THE ESTIMATES ARE FOR THE l/3-OCTAVE BAND WHOSE SOUNDS WOULD BE DETECTABLE AT GREATEST RANGE; THE SOURCE LEVEL (SL) AND CENTER FREQUENCY (F) ARE INDICATED. AT **RANGES** WHERE THE CURVES ARE SHOWN AS DASHED LINES, THE ESTIMATED RECEIVED LEVELS ARE UNRELIABLE (SEE TEXT). EXPECTED AMBIENT NOISE LEVELS (5TH, 50TH, AND 95TH PERCENTILES) ARE ALSO SHOWN FOR THE CORRESPONDING l/3-OCTAVE BAND.

Table 13. Estimated "zones of audibility" of underwater noise from nine industrial sources if they were at the ORION site, Alaskan Beaufort Sea. The 1/3-octave band that would be detectable at greatest range is considered (see Appendix D for other dominant bands). The detection threshold is assumed to equal the ambient noise level.

Industrial Source	Dir'n from Site	RL=5th %'ile Freq. (Hz)	RL (dB)	Amb. Range (km)	RL=50th %'ile Freq. (Hz)	RL (dB)	Amb. Range (km)	RL=95th %'ile Freq. (Hz)	RL (dB)	Amb. Range (km)
A. Stationary Sources										
SANDP.TUGS	E/W	300	61	>50*	1500	81	>50*	1500	93	28*
bollard	North	300	61	>50*	300	84	>50*	300	95	44*
EXPL.II.DRILL **	E/W	315	61	>50*	315	84	30*	315	96	17
	North	160	59	>50*	160	84	>50*	160	94	32*
SANDPIP.DRILL	E/W	40	56	46*	40	82	14*	40	91	6.5
	North	40	56	>50*	40	82	18*	40	91	6.8
B. Vessels Underway										
ERIK.TUG	E/W	1000	60	>50*	1000	82	>50*	1000	94	21*
underway	North	1000	60	>50*	1000	82	>50*	1000	94	23*
KIGORIAK.10KT **	E/W	315	61	>50*	800	83	46*	315	96	24*
	North	100	58	>50*	100	83	>50*	100	93	>50*
LEMEUR.10KT	E/W	40	56	>50*	40	82	43*	40	91	32*
	North	40	56	>50*	40	82	>50*	40	91	>50*
C. Intermittent Sources										
LEMEUR.ICEBR	E/W	250	60	>50*	400	85	>50*	400	96	>50*
	North	100	58	>50*	100	83	>50*	100	93	>50*
ERIK.DREDGE	E/W	750	61	>50*	1250	82	38*	250	95	16
	North	250	60	>50*	750	84	>50*	250	95	40*
ERIK.TUG	E/W	1000	60	>50*	1000	82	>50*	1000	94	34*
towing	North	1000	60	>50*	1000	82	>50*	1000	94	43*

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

**Data from the 63 Hz band were not considered for this shallow site; KIGORIAK.10KT and EXPL.II.DRILL were the two sources for which 63 Hz was an important frequency.

The estimated ranges where the received level of dredge, tug, icebreaker or drillship noise would exceed the 5th percentile of ambient noise were beyond 50 km for east/west as well as north bearings--well beyond the range where the models can be expected to be reliable.

Thus, if there were dredge, tugboat, icebreaker or drillship operations at Orion, the sounds in at least one l/3-octave band would be expected to be above average ambient levels, and potentially detectable, out to ranges of several tens of kilometers. potential ranges of audibility would be greater to the north than to the east or west. Even under conditions of high natural ambient noise (95th percentile conditions), these industrial operations would be expected to be detectable up to at least 16 km to the east or west, and farther to the north. Because of the uncertain accuracy of the propagation models for long ranges, especially to the north, the longer estimates (those >20 km) should be taken as general guidelines? not specific predictions.

In contrast, if the 40 Hz sounds recorded from the drilling operation on Sandpiper Island were introduced into the water at Orion, their levels would be expected to drop below the median ambient level within 14-18 km from Orion (Fig, 52; Table 13). They would drop below the 95th percentile ambient noise within 7 km. The comparatively low range of potential audibility of the “drilling on artificial island” sounds is attributable to two factors: (1) Their source level was 13-38 dB less than the levels of the other sounds considered here (Table 12), and (2) their expected attenuation rate in the shallow water near Orion was high because of their low frequency.

Sandpiper. -- Estimated zones of audibility around the Sandpiper site were similar to those around Orion (Table 14, Fig. 53). This was to be expected. Sandpiper and Orion are at similar water depths (15 and 14 m, respectively), and were the two westernmost sites.

Table 14. Estimated "zones of audibility" of underwater noise from nine industrial sources if they were at the SANDPIPER site, Alaskan Beaufort Sea. The l/3-octave band that would be detectable at greatest range is considered (see Appendix D for other dominant bands). The detection threshold is assumed to equal the ambient noise level.

Industrial Source	Dir'n from Site	RL=5th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=50th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=95th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)
A. Stationary Sources										
SANDP.TUGS	E/W	300	61	>50*	1500	81	>50*	1500	93	48*
bollard	North	300	61	>50*	300	84	>50*	1500	93	47*
EXPL.II.DRILL	E/W	315	61	>50*	315	84	29*	315	96	16
**	North	160	59	>50*	160	84	>50*	160	94	26*
SANDPIP.DRILL	E/W	40	56	46*	40	82	14*	40	91	6.5
	North	40	56	>50*	40	82	17*	40	91	6.8
B. Vessels Underway										
ERIK.TUG	E/W	1000	60	>50*	1000	82	>50*	1000	94	35*
underway	North	1000	60	>50*	1000	82	>50*	1000	94	36*
KIGORIAK.10KT **	E/W	315	61	>50*	800	83	>50*	800	95	26*
	North	100	58	>50*	100	83	>50*	100	93	>50*
LEMEUR.10KT	E/W	40	56	>50*	40	82	43*	40	91	32*
	North	40	56	>50*	40	82	>50*	40	91	>50*
C. Intermittent Sources										
LEMEUR.ICEBR	E/W	250	60	>50*	400	85	>50*	2000	92	>50*
	North	100	58	>50*	100	83	>50*	100	93	>50*
ERIK.DREDGE	E/W	750	61	>50*	1250	82	>50*	1250	94	24*
	North	250	60	>50*	250	84	>50*	250	95	29*
ERIK.TUG	E/W	1000	60	>50*	1000	82	>50*	1000	94	>50*
starting	North	1000	60	>50*	1000	82	>50*	1000	94	>50*

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

**Data from the 63 Hz band were not considered for this shallow site; KIGORIAK.10KT and EXPL.II.DRILL were the two sources for which 63 Hz was an important frequency.

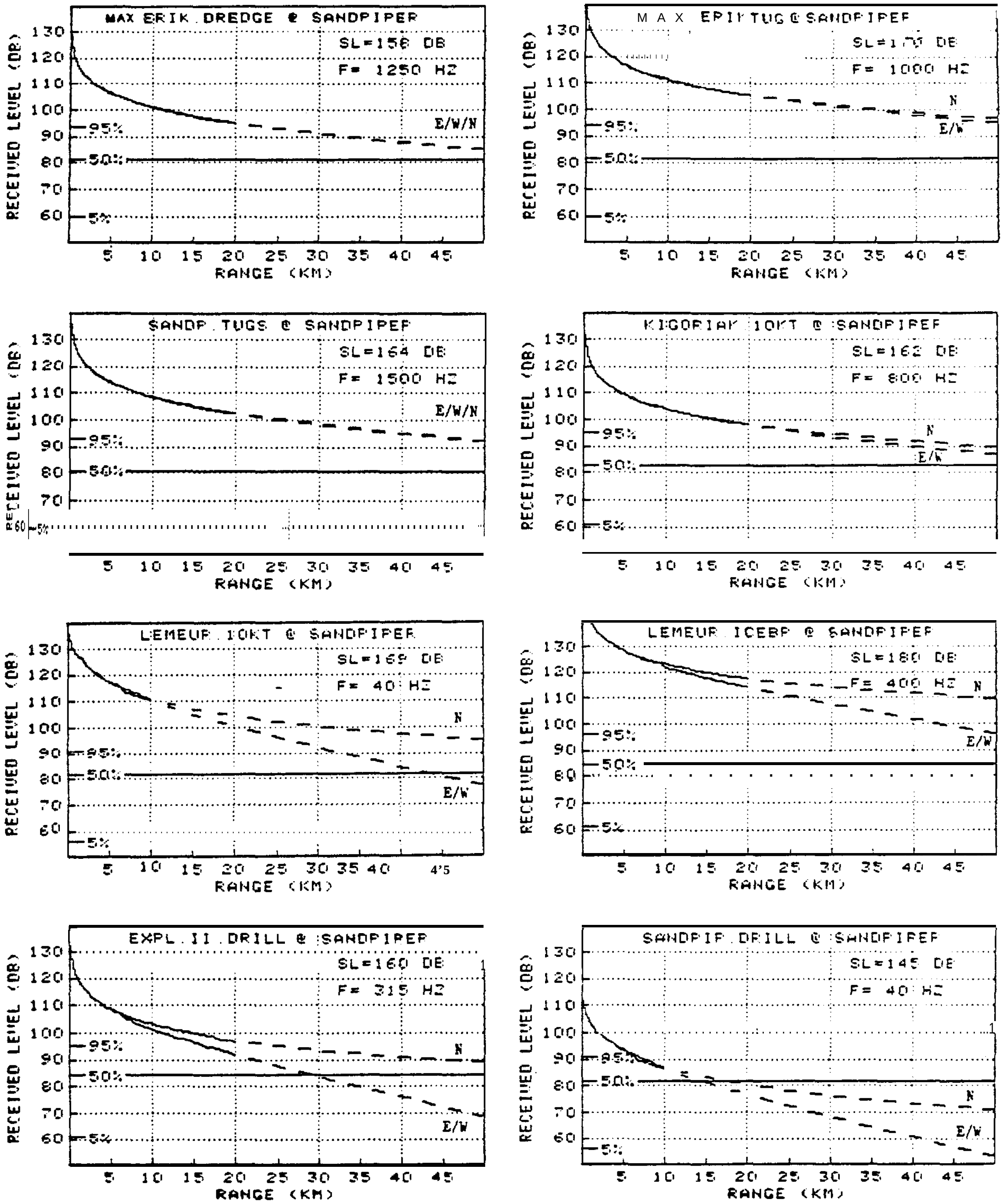


FIG. 53. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE SANDPIPER SITE IF EACH OF EIGHT INDUSTRIAL SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 52.

The dredge, tug, icebreaker or drillship sounds would be expected to exceed the median ambient noise level at all ranges within 29 to 50+ km to the east, west or north of Sandpiper. However, all of these predicted ranges exceed the range to which the sound propagation models are considered reliable. The received levels are predicted to exceed the 95th percentile ambient noise at 16 to 50+ km east or west of Sandpiper, and 26 to 50+ km north.

The 40 Hz sound from drilling on an artificial island would not be detectable nearly as far away. The received level is predicted to equal the 95% ambient at about 7 km and the median ambient at about 14-17 km (Table 14; Fig. 53), similar to the corresponding figures for the Orion site. These estimates are based, in part, on direct measurements of the 40 Hz sounds near Sandpiper Island (Greene in Johnson et al. 1986).

Hammerhead and Corona. -- These two sites are considered together because they were at similar water depths (30 and 35 m, respectively) in the middle portion of the study area. The " zone of audibility" estimates for the two sites were very similar. If the dredge, tugs, or icebreakers were operating at these sites, their noise would be expected to exceed the median ambient level in at least one l/3-octave band at all ranges within 50 km east, west or north. Their noise is predicted to exceed the 95th percentile ambient level up to 19 to 50+ km away (Fig. 54, 55; Table 15, 16). The tugs and the icebreaker pushing ice are the sources that would be audible farthest away. The zone of audibility of the drillship EXPLORER II to the east, west and north is expected to be slightly less than that of the aforementioned vessels: 45 to 50+ km under median ambient conditions, and 13-23 km under 95th percentile conditions. All of these industrial activities are expected to be audible beyond 50 km to the east, west and north under quiet 5th percentile conditions.

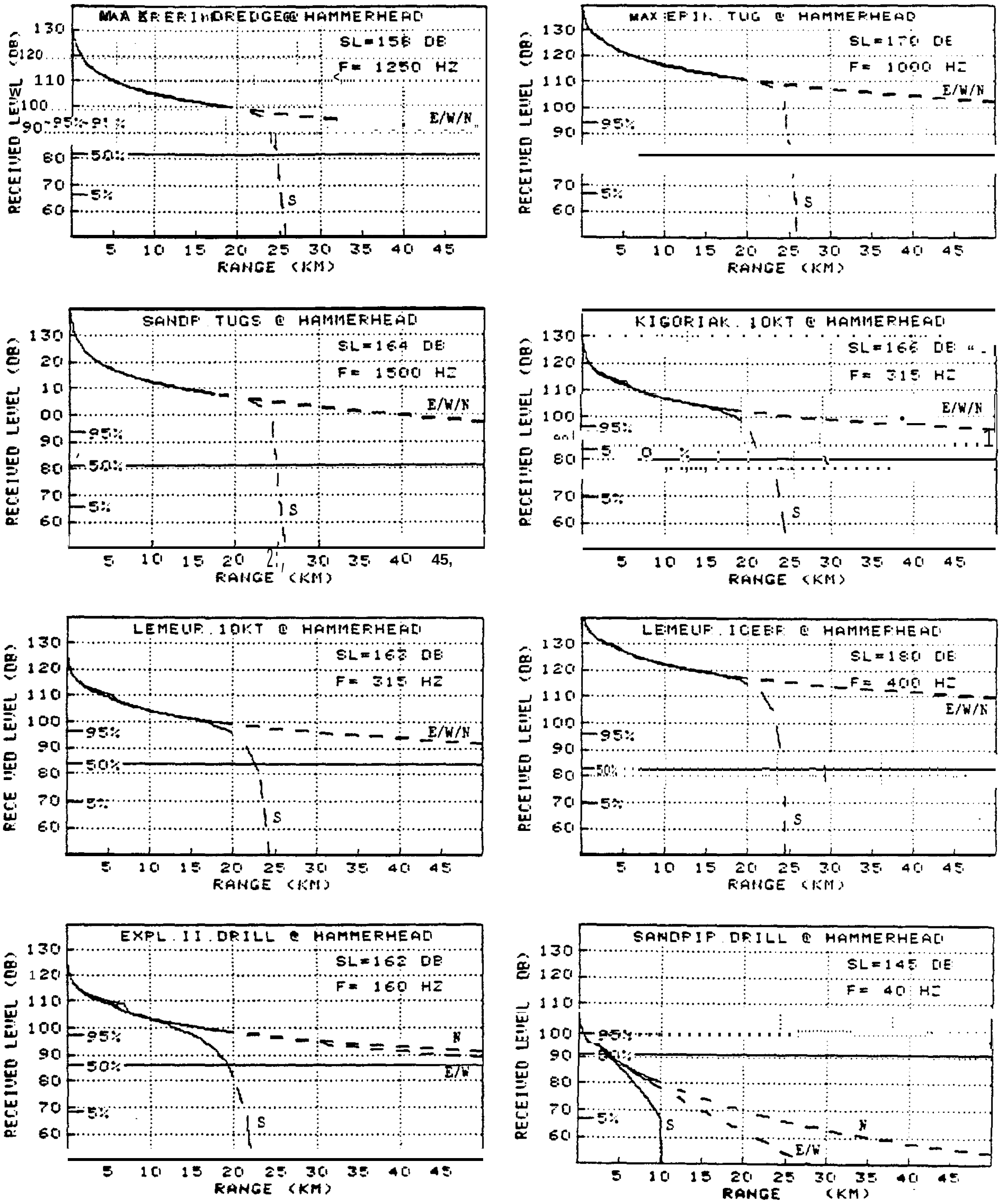


FIG. 54. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE HAMMERHEAD SITE IF EACH OF EIGHT INDUSTRIAL SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 52, EXCEPT THAT ESTIMATES FOR SOUTHWARD PROPAGATION INTO SHALLOWER WATER ARE ALSO SHOWN.

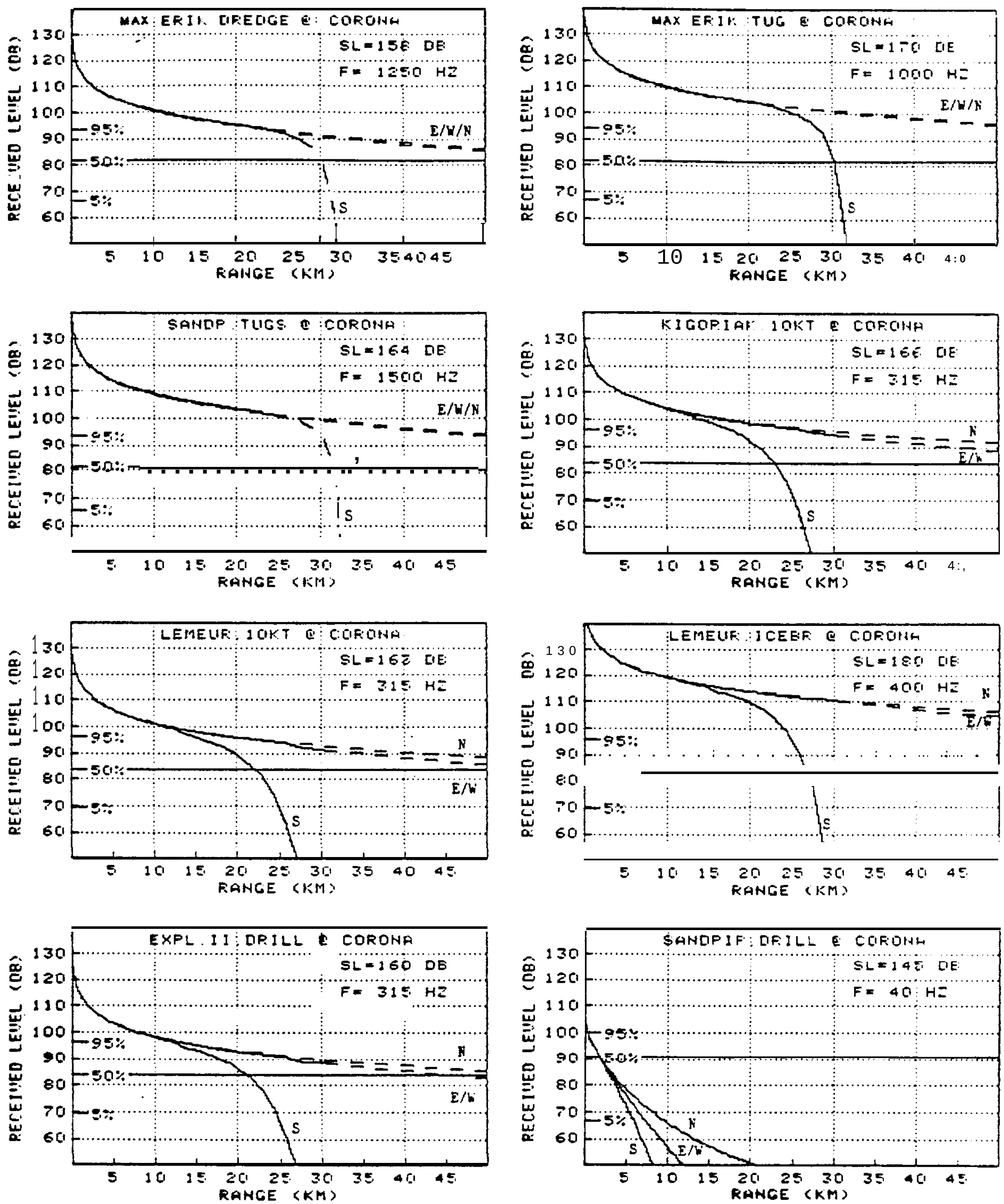


FIG. 55. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE CORONA SITE IF EACH OF EIGHT INDUSTRIAL NOISE SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 54.

Table 15. Estimated "zones of audibility" of underwater noise from nine industrial sources if they were at the HAMMERHEAD site, Alaskan Beaufort Sea. The I/s-octave band that would be detectable at greatest range is considered (see Appendix D for other dominant bands). The detection threshold is assumed to equal the ambient noise level.

Industrial Source	Dirtn from Site	RL=5th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=50th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=95th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)
A. Stationary Sources										
SANDP.TUGS bollard	South	4000	62	26*	4000	81	26*	4000	93	25*
	E/W	300	69	>50*	300	84	>50*	1500	94	>50*
	North	300	69	>50*	300	84	>50*	1500	94	>50*
EXPL.II.DRILL	South	315	69	23*	315	84	22*	315	96	18
	E/W	63	67	>50*	160	86	>50*	160	97	22*
	North	63	67	>50*	160	86	>50*	160	97	23*
SANDPIP.DRILL	South	40	67	9.9	40	91	3.4	40	100	.65
	E/W	40	67	17*	40	91	3.5	40	100	.63
	North	40	67	24*	40	91	3.8	40	100	.63
B. Vessels Underway										
ERIK.TUG underway	South	2500	64	26*	1000	82	25*	1000	94	25*
	E/W	1000	67	>50*	1000	82	>50*	1000	94	>50*
	North	1000	67	>50*	1000	82	>50*	1000	94	>50*
KIGORIAK.10KT	South	800	68	25*	800	82	25*	800	94	24*
	E/W	63	67	>50*	100	88	>50*	800	94	47*
	North	63	67	>50*	63	90	>50*	100	98	>50*
LEMEUR.10KT	South	315	69	24*	315	84	23*	315	96	20
	E/W	100	68	>50*	315	84	>50*	315	96	30*
	North	40	67	>50*	100	88	>50*	315	96	29*
C. Intermittent Sources										
LEMEUR.ICEBR	South	4000	62	26*	4000	81	26*	4000	93	26*
	E/W	100	68	>50*	100	88	>50*	100	98	>50*
	North	100	68	>50*	100	88	>50*	100	98	>50*
ERIK.DREDGE	South	1250	67	25*	1250	82	25*	1250	94	24*
	E/W	250	69	>50*	250	85	>50*	1250	94	37*
	North	250	69	>50*	250	85	>50*	1250	94	35*
ERIK.TUG starting	South	3500	63	26*	3500	81	26*	3500	93	25*
	E/W	1000	67	>50*	1000	82	>50*	1000	94	>50*
	North	1000	67	>50*	1000	82	>50*	1000	94	>50*

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

Table 16. Estimated "zones of audibility" of underwater noise from nine industrial sources if they were at the CORONA site, Alaskan Beaufort Sea. The 1/3-octave band that would be detectable at greatest range is considered (see Appendix D for other dominant bands). The detection threshold is assumed to equal the ambient noise level.

Industrial Source	Dir'n from Site	RL=5th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=50th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=95th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)
A. Stationary Sources										
SANDP.TUGS bollard	South	4000	62	34*	4000	81	33*	1500	94	30*
	E/W	300	69	>50*	300	84	>50*	1500	94	52*
	North	300	69	>50*	300	84	>50*	1500	94	48*
EXPL.II.DRILL	South	315	69	25	315	84	21	315	96	12
	E/W	160	69	>50*	315	84	45*	315	96	13
	North	63	67	>50*	315	84	>50*	315	96	13
SANDPIP.DRILL	South	40	67	5.9	40	91	1.8	40	100	.37
	E/W	40	67	7.4	40	91	1.8	40	100	.37
	North	40	67	9.5	40	91	1.9	40	100	.36
B. Vessels Underway										
ERIK.TUG underway	South	2500	64	33*	2500	81	32*	1000	94	26
	E/W	1000	67	>50*	1000	82	>50*	1000	94	34*
	North	1000	67	>50*	1000	82	>50*	1000	94	33*
KIGORIAK.10KT	South	800	68	30	800	82	28	800	94	22
	E/W	100	68	>50*	315	84	>50*	800	94	27*
	North	63	67	>50*	100	88	>50*	100	98	31*
LEMEUR.10KT	South	315	69	25	315	84	22	315	96	15
	E/W	315	69	>50*	315	84	>50*	315	96	19
	North	100	68	>50*	315	84	>50*	315	96	19
C. Intermittent Sources										
LEMEUR.ICEBR	South	4000	62	34*	4000	81	34*	4000	93	33*
	E/W	100	68	>50*	250	85	>50*	250	97	>50*
	North	100	68	>50*	100	88	>50*	4000	93	>50*
ERIK.DREDGE	South	1250	67	32*	1250	82	30*	1250	94	22
	E/W	250	69	>50*	750	82	>50*	1250	94	23
	North	250	69	>50*	250	85	>50*	1250	94	22*
ERIK.TUG starting	South	3500	63	34*	3500	81	33*	3500	93	32*
	E/W	1000	67	>50*	1000	82	>50*	1000	94	>50*
	North	1000	67	>50*	1000	82	>50*	1000	94	>50*

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

For all sources, the zone of audibility to the south of Hammerhead and Corona is expected to be less than that in other directions. This is a result of the diminishing water depth and presence of the coast to the south.

As at Orion and Sandpiper, the zone of potential audibility would be much less for the 40 Hz sounds from a hypothesized drilling operation on an artificial island. The received level is predicted to equal the 95, 50 and 5 percentile ambient values at ranges of about 0.5, 2-4 and 6-24 km, respectively (Table 15, 16; Fig. 54, 55). However, an artificial island of the type where these drilling sounds were recorded (Sandpiper, water 15 m deep) would not be constructed in the deeper water at Hammerhead or Corona.

Erik and Belcher. -- These two sites were in the deepest water of any sites studied (40 and 55 m), and were the two easternmost sites studied. The estimated zones of audibility around these sites were similar, and hence the two sites are considered together.

If a dredge, tug, icebreaker, or drillship were operating at Erik or Belcher, its sounds would be expected to exceed the median ambient level out to ranges >50 km east, west, and (for Erik) north. (Estimates for northward propagation from Belcher were not made because the standard Weston/Smith sound propagation model did not provide an adequate fit to the data for that situation-- see Section 3.3.) For at least one l/3-octave band, the noise from any of these sources is expected to exceed the 95th percentile ambient noise up to 14 to 50+ km on those bearings (Table 17, 18; Fig. 56, 57). The sounds from an ice-breaker pushing ice are expected to be detectable farther away than those from any of the other sources.

As at Hammerhead and Corona, all of these sources are expected to be audible >50 km to the east, west and north under quiet (5th percentile) conditions. Because of the diminishing

Table 17. Estimated "zones of audibility" of underwater noise from nine industrial sources if they were at the ERIK site, Alaskan Beaufort Sea. The 1/3-octave band that would be detectable at greatest range is considered (see Appendix D for other dominant bands). The detection threshold is assumed to equal the ambient noise level.

Industrial Source	Dirtn from Site	RL=5th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=50th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=95th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)
A. Stationary Sources										
SANDP.TUGS	South	4000	62	26*	1500	82	25	1500	94	18
bollard	E/W	300	69	>50*	300	84	>50*	1500	94	18
	North	300	69	>50*	300	84	>50*	1500	94	17
EXPL.II.DRILL	South	315	69	23	315	84	21	160	97	11
	E/W	63	67	>50*	315	84	>50*	63	100	15
	North	63	67	>50*	63	90	>50*	63	100	18
SANDPIP.DRILL	South	40	67	11	40	91	3.4	40	100	1.2
	E/W	40	67	21*	40	91	3.5	40	100	1.2
	North	40	67	39*	40	91	3.5	40	100	1.2
B. Vessels Underway										
ERIK.TUG	South	2500	64	25	1000	82	24	1000	94	16
underway	E/W	1000	67	>50*	1000	82	>50*	1000	94	15
	North	1000	67	>50*	1000	82	>50*	1000	94	15
KIGORIAK.10KT	South	800	68	25	800	82	23	315	96	18
	E/W	63	67	>50*	100	88	>50*	200	97	30
	North	63	67	>50*	63	90	>50*	100	98	41*
LEMEUR.10KT	South	315	69	23	315	84	21	315	96	15
	E/W	100	68	>50*	315	84	>50*	315	96	17
	North	40	67	>50*	315	84	>50*	40	100	17
C. Intermittent Sources										
LEMEUR.ICEBR	South	4000	62	26*	4000	81	26*	4000	93	25*
	E/W	100	68	>50*	4000	81	>50*	100	98	>50*
	North	100	68	>50*	100	88	>50*	100	98	>50*
ERIK.DREDGE	South	1250	67	25	1250	82	23	250	97	13
	E/W	250	69	>50*	250	85	>50*	250	97	14
	North	250	69	>50*	250	85	>50*	250	97	14
ERIK.TUG	South	3500	63	26*	3500	81	25	1000	94	23
starting	E/W	1000	67	>50*	1000	82	>50*	1000	94	32
	North	1000	67	>50*	1000	82	>50*	1000	94	30*

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

Table 18. Estimated "zones of audibility" of underwater noise from nine industrial sources if they were at the BELCHER site, Alaskan Beaufort Sea. The 1/3-octave band that would be detectable at greatest range is considered (see Appendix D for other dominant bands). The detection threshold is assumed to equal the ambient noise level.

Industrial Source	Dir'n from Site	RL=5th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=50th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)	RL=95th %'ile Amb. Freq. (Hz)	RL (dB)	Range (km)
A. Stationary Sources										
SANDP.TUG	SE/W	300	69	50	300	84	>50	300	96	30
bollard	South	1500	66	41	1500	82	40	300	96	28
EXPL.II.DRILL	E/W	63	67	>50*	160	86	>50	160	97	22
	South	315	69	38	315	84	36	160	97	20
SANDPIP.DRILL	E/W	40	67	24*	40	91	4.6	40	100	1.5
	South	40	67	15	40	91	4.3	40	100	1.5
B. Vessels Underway										
ERIK.TUG	E/W	1000	67	>50	1000	82	>50	1000	94	19
underway	South	2500	64	40*	1000	82	39	1000	94	20
KIGORIAK.10KT	E/W	63	67	>50*	63	90	>50	*200	97	>50
South		800	68	40	800	82	39	315	96	32
LEMEUR.10KT	E/W	100	68	>50	100	88	>50	315	96	30
	South	315	69	38	315	84	37	315	96	28
C. Intermittent Sources										
LEMEUR.ICEBR	E/W	100	68	>50	100	88	>50	100	98	>50
	South	2000	65	41*	2000	81	41*	400	96	38
ERIK.DREDGE	E/W	250	69	>50	250	85	>50	250	97	25
	South	1250	67	40	750	82	38	250	97	24
ERIK.TUG	E/W	1000	67	>50	1000	82	>50	1000	94	38
starting	South	3500	63	41*	1000	82	40	1000	94	36

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

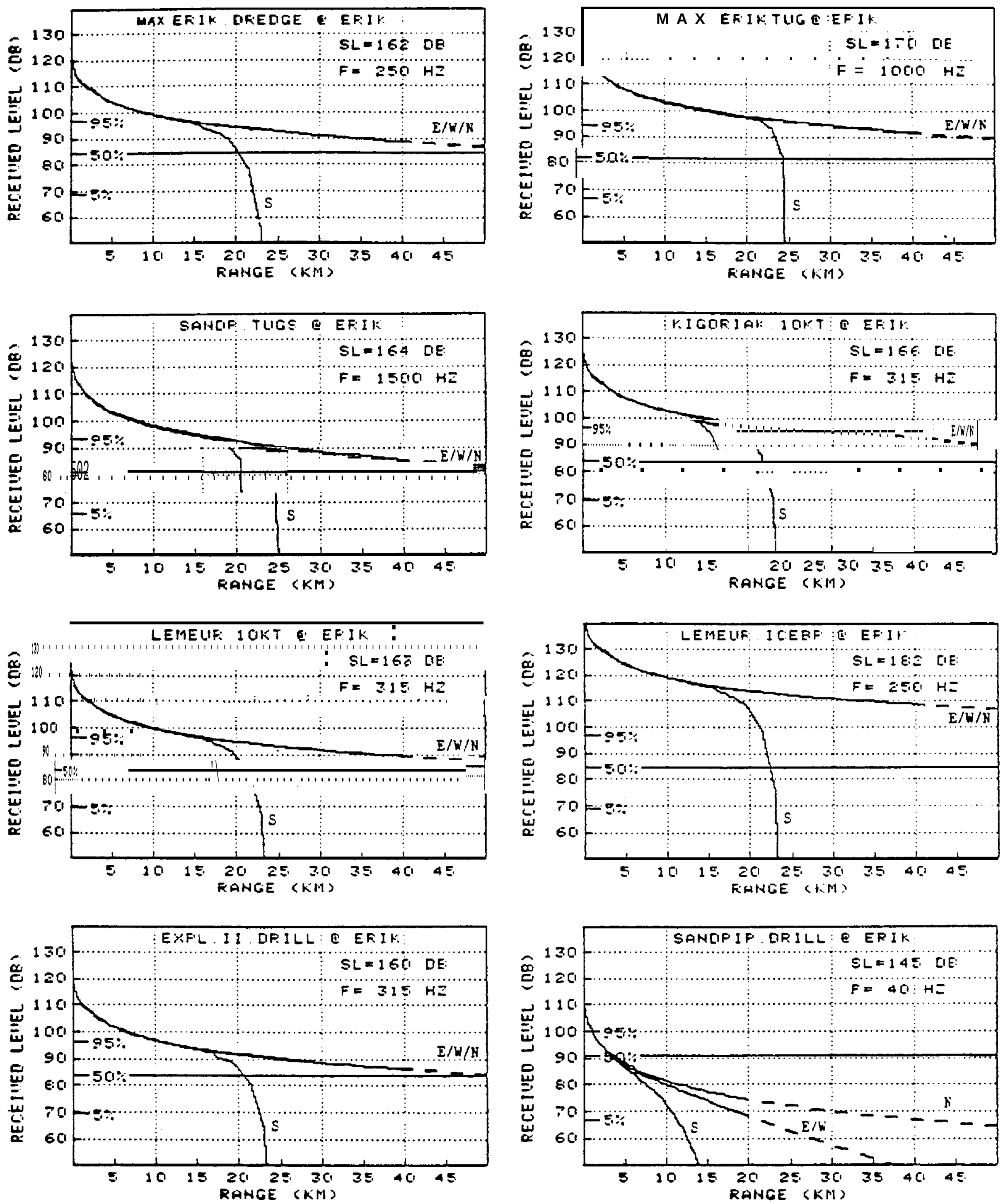


FIG. 56. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE ERIK SITE IF EACH OF EIGHT INDUSTRIAL SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 54.

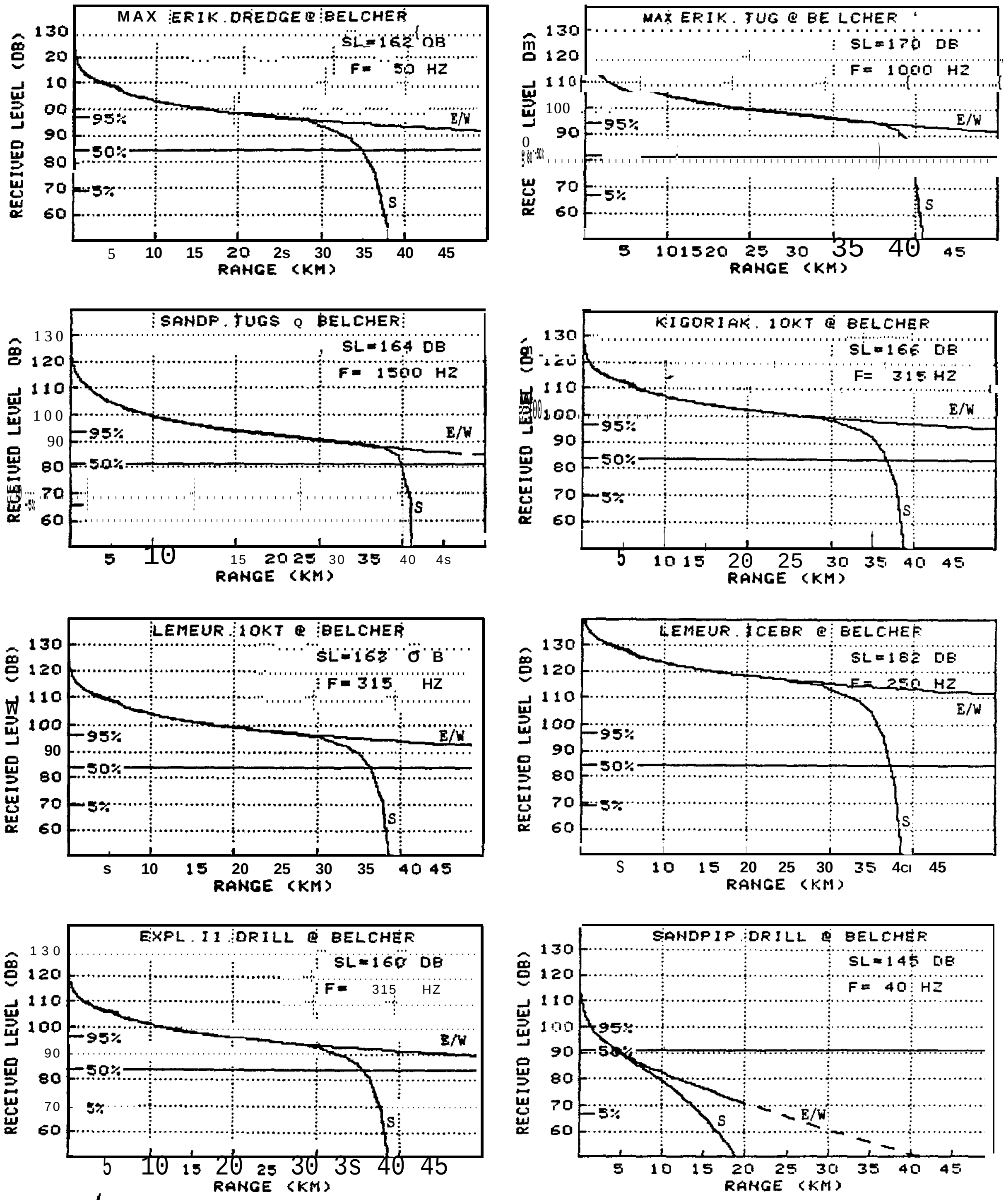


FIG. 57. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE BELCHER SITE IF EACH OF EIGHT INDUSTRIAL SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 54, EXCEPT THAT NO ESTIMATES FOR NORTHWARD PROPAGATION WERE MADE.

water depth to the south, all sources would be detectable less far to the south than to other directions. The expected zones of audibility to the south are greater at Belcher than at Erik because Belcher is farther offshore.

If an artificial island of the type at Sandpiper could be constructed at Erik or Belcher, 40 Hz drilling sounds would be expected to be detectable out to at least 1.2-1.5 km 95% of the time, and to 3.5-4.5 km 50% of the time. The potential zone of audibility under quiet conditions (5th percentile ambient noise) is predicted to be considerably greater, especially to the north (11-39 km; Table 17, 18). However, artificial islands of the type at Sandpiper, where these drilling sounds were recorded, have not been constructed in water deeper than about 18 m.

Summary. -- Our estimates of the zone of potential audibility have assumed that whales might detect an industrial noise if the received level in any one 1/3-octave band is as intense as the ambient noise in that band. Based on this criterion, the dredge, tugs, icebreakers, or drillship were potentially detectable under average noise conditions up to several tens of kilometers east, west or north of most sites. Even when the ambient noise was higher, at the 95th percentile level, the least noisy of these sources (the drillship) would be potentially detectable 11-32 km away. Under 95th percentile conditions, the noisiest source (icebreaker pushing ice) would be detectable 50+ km east, west or north of each site that we considered.

In contrast, the 40 Hz noise from drilling on an artificial island was not expected to be detectable nearly as far away from any of the sites under average ambient noise conditions. At shallow sites where artificial islands of this type might be used, the sounds were not expected to be detectable more than about 14-18 km away under average conditions.

It is important to note that these estimates are subject to considerable uncertainty. Most of the longer estimates, especially those to the north of the sites, are based on application of the Weston/Smith sound propagation models at ranges beyond those for which BBN obtained data on transmission loss rates. Even within the ranges where the models are likely to be reliable, expected received levels often diminish slowly with increasing range. Thus, small errors in assumptions about propagation loss, ambient noise levels, or the hearing abilities of whales could cause major errors in estimated zones of potential audibility.

At Corona, for example, the potential zone of audibility of the drillship under median ambient conditions has been estimated as 45 to 50+ km east, west and north (Table 16). However, the zone would be reduced to 17-18 km if the industrial noise must be 10 dB rather than 0 dB above ambient in order to be heard (Appendix D). The zone would also be reduced to 17-18 km when the ambient noise level is 10 dB higher than the average assumed here. For the stronger noise sources (tugs, icebreaker pushing ice), the zone of audibility under median ambient conditions at Corona would remain above 50 km even if the hearing threshold were 10 dB above ambient (Appendix D). Data on the hearing abilities of baleen whales will be needed in order to resolve such uncertainties about the zone of audibility.

3.4.3 Zones of responsiveness for bowhead whales

The sensitivity of bowhead whales to drilling and construction noise is apparently quite variable. Some individuals showed avoidance reactions during playback tests when the signal-to-noise ratio (industrial noise : ambient noise) was as low as 16-24 dB in the 1/3-octave band of maximum S:N. Others showed no obvious reaction to playbacks when S:N was over 30 dB (see Table 5, Fig. 11B). In addition, a considerable number of bowheads have been seen close enough to drillships and dredges to experience S:N ratios as high as 15 dB and 29 dB, respectively, and some have been seen even closer to these industrial activities (Table 4, Fig. 11B). Sensitivity is apparently at least as variable if measured in terms of absolute received levels rather than S:N ratios (Tables 4, 5; Fig. 11A).

Thus, no single threshold of responsiveness criterion can be identified for bowheads. We have instead calculated the ranges from six industrial activities and six sites at which the S:N ratio is expected to be 20 dB and 30 dB. These two criteria are considered to represent situations in which overt responses (such as avoidance) would be expected from a minority of bowheads (20 dB) and roughly half of the bowheads (30 dB). In each case, the frequency band under consideration is the l/3-octave band in which these S:N ratios would be found at greatest range. (Results for other l/3-octave bands with high S:N are given in Appendix D.) We also present the ranges where the absolute received level in this l/3-octave band would be 110 dB--an estimate of the absolute noise level at which roughly half of the bowheads (and gray whales) may respond. Table 6 in Section 2.3 summarizes the many assumptions involved in selecting these criteria of responsiveness.

The ambient noise considered in most cases is the median ambient noise, as derived in Section 3.1. The 20 dB and 30 dB S:N situations would be found at greater ranges under conditions of low ambient noise, and at lesser ranges under conditions of high ambient noise. For most sites, only the “median ambient” situation is discussed below. However, for the Corona site we do discuss the effects of variations in ambient level and in the rate of sound transmission loss (Sec. 3.4.5). For other sites, the effects of variations in ambient noise on the range where S:N is 20 dB or 30 dB can be seen in Figures 52 - 57, where 5th and 95th percentile ambient noise levels are shown. Variations in ambient noise level have no effect on the range where the absolute received level is 110 dB.

Zone of responsiveness calculations have been done for each combination of the usual six sites and six industrial sources--the three stationary sources and the three vessels underway (Table 12). The "vessels underway" analyses assume that the vessel noise is more or less constant as received by the whales. The case of a vessel heading directly toward the whales is specifically excluded; whales appear to be especially sensitive to such situations (see Sec. 3.5, later). Also excluded are the three intermittent sources, since it is not known whether the "threshold of responsiveness" criteria mentioned above are applicable to industrial activities with variable source levels (see Sec. 2.3 and 3.6).

Orion and Sandpiper. -- These two sites are considered together because of their similar shallow water depths (14 and 15 m), similar locations (the two most westerly sites), and similar estimated zones of responsiveness. Considering the tugboats, icebreakers underway, and EXPLORER II drillship, the noise level in at least one l/3-octave band would be expected to be at least 20 dB above the median ambient level at all ranges out to 9-18 km east or west of Orion, and 7.5-23 km east or west of Sandpiper (Table 19, 20). Of these sources, the drillship (if it could operate in such shallow water) and, at Orion, the tug underway would be expected to have the smallest zones of responsiveness; the stationary tugs and icebreakers underway generally would have larger zones of responsiveness. Corresponding distances to the north are expected to be somewhat larger for most sources: 9-33 km from Orion and 10-32 km from Sandpiper. It should be noted that estimated ranges exceeding about 20 km (sometimes less) were beyond the ranges where direct measurements of transmission loss were available, and the accuracy of these estimates is uncertain.

Table 19. Estimated "zones of responsiveness" for bowhead whales to underwater noise from six industrial sources if they were at the ORION site, Alaskan Beaufort Sea. The I/s-octave band that would be expected to cause a response at greatest range is considered (see Appendix D for other dominant bands). Few bowheads would be expected to react at ranges exceeding that where the S:N ratio (industrial noise : ambient noise) is 20 dB. Roughly half would be expected to react at 30 dB. The range where the received level would be 110 dB re 1 μPa is an alternative estimate of the radius of roughly 50% response. Radii of responsiveness for 20 dB and 30 dB S:N criteria assume median ambient conditions.

Industrial Source	Dirtn from Site	S:N = 20 dB Freq. (Hz)	MedAmb (dB)	Range (km)	S:N = 30 dB Freq. (Hz)	MedAmb (dB)	Range (km)	RL = 110 dB Freq. (Hz)	Range (km)
A. Stationary Sources									
SANDP.TUGS	E/W	1500	81	13	300	84	4.6	300	6.8
bollard	North	300	84	17	300	84	4.7	300	8.2
EXPL.II.DRILL	E/W	315	84	8.8	160	84	3.6	315	5.3
**	North	160	84	12	160	84	3.9	160	5.9
SANDPIP.DRILL	E/W	40	82	1.8	40	82	.19	40	.29
	North	40	82	1.7	40	82	.19	40	.29
B. Vessels Underway									
ERIK.TUG	E/W	1000	82	9.1	1000	82	2.4	1000	3.2
underway	North	1000	82	9.1	1000	82	2.4	1000	3.2
KIGORIAK.10KT	E/W	315	84	14	100	83	7.3	315	9.2
**	North	100	83	33*	100	83	12	100	16
LEMEUR.10KT	E/W	40	82	18*	40	82	8.3	40	10
	North	40	82	27*	40	82	9.3	40	11*

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

**Data from the 63 Hz band were not considered for this shallow site; KIGORIAK.10KT and EXPL.II.DRILL were the two sources for which 63 Hz was an important frequency.

Table 20. Estimated "zones of responsiveness" for bowhead whales to underwater noise from six industrial sources if they were at the SANDPIPER site, Alaskan Beaufort Sea. The 1/3-octave band that would be expected to cause a response at greatest range is considered (see Appendix D for other dominant bands). Few bowheads would be expected to react at ranges exceeding that where the S:N ratio (industrial noise : ambient noise) is 20 dB. Roughly half would be expected to react at 30 dB. The range where the received level would be 110 dB re 1 µPa is an alternative estimate of the radius of roughly 50% response. Radii of responsiveness for 20 dB and 30 dB S:N criteria assume median ambient conditions.

Industrial Source	Dir'n from Site	S:N = 20 dB Freq. (Hz)	S:N = 20 dB MedAmb (dB)	S:N = 20 dB Range (km)	S:N = 30 dB Freq. (Hz)	S:N = 30 dB MedAmb (dB)	S:N = 30 dB Range (km)	RL = 110 dB Freq. (Hz)	RL = 110 dB Range (km)
A. Stationary Sources									
SANDP.TUGS	E/W	1500	81	23*	1500	81	7.3	1500	8.3
bollard	North	1500	81	23*	1500	81	7.1	1500	8.1
EXPL.II.DRILL	E/W	160	84	7.5	160	84	3.3	160	4.5
**	North	160	84	9.8	160	84	3.6	160	5.0
SANDPIP.DRILL	E/W	40	82	1.8	40	82	.19	40	.29
	North	40	82	1.8	40	82	.19	40	.29
B. Vessels Underway									
ERIK.TUG	E/W	1000	82	15	1000	82	4.2	1000	5.5
underway	North	1000	82	15	1000	82	4.1	1000	5.4
KIGORIAK.10KT	E/W	100	83	13	100	83	8.3	100	9.7
**	North	100	83	32*	100	83	12	100	16
LEMEUR.10KT	E/W	40	82	18*	40	82	8.3	40	10
	North	40	82	25*	40	82	8.9	40	11*

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

**Data from the 63 Hz band were not considered for this shallow site; KIGORIAK.10KT and EXPL.II.DRILL were the two sources for which 63 Hz was an important frequency.

The 40 Hz sounds from drilling on an artificial island were excluded from the above paragraph. They represent the weakest sources of continuous noise studied during this project (Table 12). The received noise level would be 20+ dB above the median ambient only out to about 1.8 km from the artificial island. The small radius within which S:N would be >20 dB was partly attributable to the low source level of these sounds, and partly to their low frequency and resulting rapid attenuation in the shallow water near Orion and Sandpiper.

Beyond the ranges where average S:N would be <20 dB, we would expect few bowhead whales to react to the industrial noise. Many individuals would not react unless they were within some considerably closer range where S:N exceeded 20 dB by a substantial margin.

If a tugboat, icebreaker underway, or drillship operated at Orion or Sandpiper under median ambient noise conditions, the 30 dB S:N level, where roughly half of the bowheads are likely to react, is expected to occur 2.4-12 km away. The corresponding value for drilling on the artificial island was 0.2 km. The following list summarizes these 30 dB S:N values, considering propagation to the east, west and north, and compares them with values based on the 20 dB S:N and 110 dB absolute received level criteria:

Sources	20 dB S:N	30 dB S:N	110 dB
1. Two tugs, bollard	13-23 km	5-7 km	7-8 km
2. Drillship	8-12	3-4	5-6
3. Drilling on artificial island	1.8	0.2	0.3
4. Tug underway	9-15	2-4	3-5
5. Icebreakers underway	13-33	7-12	9-16

Results based on the 110 dB absolute noise level criterion were, in every case, intermediate between those based on the 20 and 30 dB S:N criteria, but generally closer to the 30 dB S:N values (Tables 19, 20).

The estimated zones of responsiveness based on the "110 dB absolute level" criterion are unaffected by changes in ambient noise level. However, the estimated ranges of responsiveness based on S:N criteria depend strongly on the natural noise level. Since the 95th percentile values of ambient noise are about 10 dB above the median values (Sec. 3.1), the 20 dB S:N ranges on a day with high natural ambient noise would be similar to the 30 dB S:N ranges summarized above for a day with median ambient noise. Similarly, the 30 dB S:N ranges on a noisy day would be similar to the 40 dB S:N ranges on an average day; the 40 dB ranges are given in Appendix D. Since the 5th percentile values of ambient noise are more than 20 dB below the median values, the 20 dB S:N ranges on a quiet day would exceed the 0 dB ranges ("zone of audibility") on an average day; the 0 dB ranges were >50 km for most industrial sources (Tables 13, 14). Again, most range estimates exceeding about 20 km are beyond the range of reliability of the sound propagation models.

Hammerhead and Corona. -- The zones of potential responsiveness around Hammerhead and Corona differed from those around Orion and Sandpiper, in part because of the greater water depth (30-35 m). Since some bowheads migrate westward south of these sites, radii of responsiveness have been estimated for southerly as well as east/west and northerly bearings. The results for all directions of propagation are summarized below:

Sources	20 dB S:N	30 dB S:N	110 dB
1. Two tugs, bollard	23-34 km	7-12 km	9-14 km
2. Drillship	5-8	1	3-8
3. Drilling on artificial island	0.05	0.02	0.06
4. Tug underway	13-28	3-8	4-11
5. Icebreakers underway	7-25	2-8	4-20

The estimated ranges where S:N would be 20 dB on an average day, i.e., where a minority of the bowheads would be expected to react, ranged from 23 to 34 km from two tugs in bollard condition down to 5-8 km from the drillship and 0.05 km from the artificial island with drilling (Tables 21, 22).

The ranges where S:N would be 30 dB on an average day, i.e., where roughly half the bowheads would be expected to react, were 1-2 km for LEMEUR underway and the drillship; 3-8 km for KIGORIAK and the tug underway; and 7-12 km for bollard tugs. The 110 dB absolute noise level was calculated to occur somewhat farther from the industrial sources than the 30 dB S:N ratio, but generally less far away than the 20 dB S:N ratio (see list above).

The predicted zone of responsiveness to 40 Hz sounds from drilling on an artificial island was smaller for Hammerhead and Corona than for Orion or Sandpiper--no more than 60 m for any of the three response criteria. It should be noted that an artificial island of the type where these drilling sounds were recorded (Sandpiper, 15 m water depth) is not likely to be built in water as deep as that at Hammerhead or Corona.

Erik and Belcher. -- These two sites are considered together. They were the easternmost and deepest (40 and 55 m) sites.

Table 21. Estimated "zones of responsiveness" for bowhead whales to underwater noise from six industrial sources if they were at the HAMMERHEAD site, Alaskan Beaufort Sea. The 1/3-octave band that would be expected to cause a response at greatest range is considered (see Appendix D for other dominant bands). Few bowheads would be expected to react at ranges exceeding that where the S:N ratio (industrial noise : ambient noise) is 20 dB. Roughly half would be expected to react at 30 dB. The range where the received level would be 110 dB re 1 µPa is an alternative estimate of the radius of roughly 50% response. Radii of responsiveness for 20 dB and 30 dB S:N criteria assume median ambient conditions.

Industrial Source	Dir'n from Site	S:N = 20 dB Freq. (Hz)	S:N = 20 dB MedAmb (dB)	S:N = 20 dB Range (km)	S:N = 30 dB Freq. (Hz)	S:N = 30 dB MedAmb (dB)	S:N = 30 dB Range (km)	RL = 110 dB Freq. (Hz)	RL = 110 dB Range (km)
A. Stationary Sources									
SANDP.TUGS	South	1500	82	23*	1500	82	12	1500	14
bollard .	E/W	1500	82	34*	1500	82	11	1500	13
	North	1500	82	33*	1500	82	11	1500	13
EXPL.II.DRILL	South	160	86	7.4	63	90	1.3	63	5.9
	E/W	63	90	6.9	63	90	1.2	63	6.9
	North	63	90	8.2	63	90	1.2	63	8.2
SANDPIP.DRILL	south	40	91	.05	40	91	.02	40	.06
	E/W	40	91	.05	40	91	.02	40	.06
	North	40	91	.05	40	91	.02	40	.06
B. Vessels Underway									
ERIK.TUG	South	1000	82	23*	1000	82	8.0	1000	11
underway	E/W	1000	82	28*	1000	82	7.7	1000	10
	North	1000	82	27*	1000	82	7.6	1000	9.9
KIGORIAK.10KT	South	800	82	19	100	88	7.2	100	12
	E/W	100	88	21*	100	88	7.9	100	18
	North	100	88	25*	100	88	8.1	100	20
LEMEUR.10KT	South	315	84	11	100	88	2.2	100	6.9
	E/W	315	84	10	100	88	2.0	100	7.0
	North	315	84	10	100	88	1.9	100	7.1

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

Table 22. Estimated "zones of responsiveness" for bowhead whales to underwater noise from six industrial sources if they were at the CORONA site, Alaskan Beaufort Sea. The l/3-octave band that would be expected to cause a response at greatest range is considered (see Appendix D for other dominant bands). Few bowheads would be expected to react at ranges exceeding that where the S:N ratio (industrial noise : ambient noise) is 20 dB. Roughly half would be expected to react at 30 dB. The range where the received level would be 110 dB re 1 µPa is an alternative estimate of the radius of roughly 50% response. Radii of responsiveness for 20 dB and 30 dB S:N criteria assume median ambient conditions.

Industrial Source	Dir'n from Site	S:N = 20 dB Freq. (Hz)	S:N = 20 dB MedAmb (dB)	S:N = 20 dB Range (km)	S:N = 30 dB Freq. (Hz)	S:N = 30 dB MedAmb (dB)	S:N = 30 dB Range (km)	RL = 110 dB Freq. (Hz)	RL = 110 dB Range (km)
A. Stationary Sources									
SANDP.TUGS	South	1500	82	24	1500	82	7.3	1500	9.0
bollard	E/W	1500	82	24*	1500	82	7.2	1500	8.8
	North	1500	82	23*	1500	82	7.0	1500	8.5
EXPL.II.DRILL	South	315	84	4.6	315	84	1.1	63	3.2
	E/W	315	84	4.6	315	84	1.1	63	3.3
	North	315	84	4.6	315	84	1.1	63	3.5
SANDPIP.DRILL	South	40	91	.05	40	91	.02	40	.06
	E/W	40	91	.05	40	91	.02	40	.06
	North	40	91	.05	40	91	.02	40	.06
B. Vessels Underway									
ERIK.TUG	South	1000	82	14	1000	82	3.4	1000	4,5
underway	E/W	1000	82	13	1000	82	3.3	1000	4.4
	North	1000	82	13	1000	82	3.3	1000	4.4
KIGORIAK.1OKT	South	800	82	11	100	88	4.7	100	7.2
	E/W	315	84	10	100	88	4.6	100	8.3
	North	100	88	11	100	88	4.2	100	9.1
LEMEUR.1OKT	South	315	84	6.9	315	84	1.7	100	4.6
	E/W	315	84	7.0	315	84	1.7	100	4.5
	North	315	84	6.9	315	84	1.7	100	4.0

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

If the drillship were operating at Erik or Belcher, its sounds would be expected to exceed the median ambient level by 20 dB out to ranges 5-7 km (Tables 23, 24). These are the approximate ranges at which we would expect the most sensitive bowheads to respond to the onset of industrial sounds. The corresponding radius of responsiveness around tugs (bollard or underway) would be similar--about 5-10 km. The estimated radius around icebreakers underway would be somewhat larger--about 6-12 km at Erik and 10-21 km at Belcher. As at other sites, the smallest radius of responsiveness would be around the drilling operation on an artificial island (0.1 to 0.24 km). The results for all directions of propagation are:

Sources	20 dB S:N	30 dB S:N	110 dB
1. Two tugs, bollard	6-10 km	1.6 km	2-4 km
2. Drillship	5-7	1-2	5-8
3. Drilling on artificial island	0.1-0.24	0.025	0.2
4. Tug underway	5-6.5	1.1	1.7
5. Icebreakers underway	6-21	1.6-6	5-17

Roughly half of the bowheads would likely respond at ranges where S:N would be about 30 dB on an average day, or where the received level would be 110 dB. S:N would be 30 dB about 1-2 km from the drillship and tugs, and 1.6-6 km from icebreakers underway. Corresponding values based on the 110 dB received level criterion were usually intermediate between the 30 dB and 20 dB S:N values, but for some sources were similar to the 20 dB S:N values (see list above, and Tables 23, 24).

Summary. -- The radius where the predicted signal-to-noise (S:N) ratio is 30 dB in the l/3-octave band of highest S:N is probably the best estimate of the average zone of potential responsiveness of bowhead whales to sources of more-or-less

Table 23. Estimated "zones of responsiveness" for bowhead whales to underwater noise from six industrial sources if they were at the ERIK site, Alaskan Beaufort Sea. The l/3-octave band that would be expected to cause a response at greatest range is considered (see Appendix D for other dominant bands). Few bowheads would be expected to react at ranges exceeding that where the S:N ratio (industrial noise : ambient noise) is 20 dB. Roughly half would be expected to react at 30 dB. The range where the received level would be 110 dB re 1 µPa is an alternative estimate of the radius of roughly 50% response. Radii of responsiveness for 20 dB and 30 dB S:N criteria assume median ambient conditions.

Industrial Source	Dir'n from Site	S:N = 20 dB Freq. (Hz)	S:N = 20 dB MedAmb (dB)	S:N = 20 dB Range (km)	S:N = 30 dB Freq. (Hz)	S:N = 30 dB MedAmb (dB)	S:N = 30 dB Range (km)	RL = 110 dB Freq. (Hz)	RL = 110 dB Range (km)
A. Stationary Sources									
SANDP.TUGS bollard	South	1500	82	6.5	1500	82	1.5	300	2.5
	E/W	1500	82	6.3	1500	82	1.5	300	2.4
	North	1500	82	6.1	1500	82	1.5	300	2.2
EXPL.II.DRILL	South	63	90	4.8	63	90	1.3	63	4.9
	E/W	63	90	4.9	63	90	1.3	63	5.1
	North	63	90	5.0	63	90	1.2	63	5.1
SANDPIP.DRILL	South	40	91	.10	40	91	.02	40	.14
	E/W	40	91	.10	40	91	.02	40	.13
	North	40	91	.10	40	91	.02	40	.13
B. Vessels Underway									
ERIK.TUG underway	South	1000	82	5.3	1000	82	1.2	1000	1.6
	E/W	1000	82	5.2	1000	82	1.2	1000	1.6
	North	1000	82	5.1	1000	82	1.1	1000	1.6
KIGORIAK.10KT	South	200	85	10	100	88	3.0	63	8.3
	E/W	100	88	11	100	88	3.0	63	10
	North	100	88	12	100	88	3.0	63	11
LEMEUR.10KT	South	315	84	5.7	40	91	1.6	40	5.2
	E/W	315	84	5.6	40	91	1.6	40	5.7
	North	40	91	5.8	40	91	1.6	40	6.2

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

Table 24. Estimated "zones of responsiveness" for bowhead whales to underwater noise from six industrial sources if they were at the BELCHER site, Alaskan Beaufort Sea. The l/3-octave band that would be expected to cause a response at greatest range is considered (see Appendix D for other dominant bands). Few bowheads would be expected to react at ranges exceeding that where the S:N ratio (industrial noise : ambient noise) is 20 dB. Roughly half would be expected to react at 30 dB. The range where the received level would be 110 dB re 1 µPa is an alternative estimate of the radius of roughly 50% response. Radii of responsiveness for 20 dB and 30 dB S:N criteria assume median ambient conditions.

Industrial Source	Dir'n from Site	S:N = 20 dB Freq. (Hz)	MedAmb (dB)	Range (km)	S:N = 30 dB Freq. (Hz)	MedAmb (dB)	Range (km)	RL = 110 dB Freq. (Hz)	Range (km)
A. Stationary Sources									
SANDP.TUGS	E/W	300	84	10	1500	82	1.7	300	3.8
bollard	South	300	84	10	1500	82	1.7	300	4.2
EXPL.II.DRILL	E/W	63	90	7.4	63	90	1.9	63	7.6
	South	63	90	7.2	63	90	1.9	63	7.3
SANDPIP.DRILL	E/W	40	91	.24	40	91	.03	40	.29
	South	40	91	.24	40	91	.03	40	.29
B. Vessels Underway									
ERIK.TUG	E/W	1000	82	6.3	1000	82	1.1	1000	1.7
underway	South	1000	82	6.5	1000	82	1.1	1000	1.8
KIGORIAK.10KT	E/W	100	88	21	100	88	5.9	100	17
	South	200	85	18	100	88	5.9	100	14
LEMEUR.10KT	E/W	315	84	10	40	91	2.2	40	7.3
	South	315	84	10	40	91	2.2	40	6.6

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

continuous noise. However, it is emphasized that some bowheads apparently do not react unless S:N is more than 30 dB, whereas others react to S:N values as low as 20 dB (Tables 4, 5; see also Richardson and Malme 1986). It is also emphasized that the zones of responsiveness estimated here depend on many assumptions, and are expected to vary from time to time even for a single site and industrial activity (see Sec. 2.3 and 3.4.5). It is further emphasized that the calculated zones of responsiveness for vessels underway do not apply to vessels that are directly and rapidly approaching the whales (cf. Sec. 3.5).

For whales east or west of the six sites considered here, the predicted distances where S:N would be 30 dB on an average day ranged, depending on type of industrial noise and site, from about 20 m to 11 km. Of the six sources considered here, the icebreakers underway and tugboats usually were the sources with the largest zones of potential responsiveness (Table 25). Drilling on an artificial island was the source with the smallest zones, ranging from about 20 to 200 m. Based on this 30 dB S:N criterion, the drillship had radii of responsiveness of 1.1-3.6 km.

Another possible criterion of responsiveness is the 110 dB absolute noise level, again considering the 1/3-octave band of highest S:N. The predicted zones of responsiveness based on the "110 dB absolute noise level" criterion are somewhat larger than those based on the "30 dB S:N" criterion, but usually are somewhat less than those based on the "20 dB S:N" criterion (Table 25). For noise propagation to the east or west, predicted radii of responsiveness based on the 110 dB criterion ranged from 4.5 to 18 km for the icebreakers underway, 1.6 to 13 km for tugs, 3.3 to 7.6 km for the drillship, and 60 to 290 m for the drilling operation on an artificial island (the weakest source).

Table 25. Summary of predicted "zones of responsiveness" (in km) for whales east or west of six sites if those sites were occupied by one of six industrial activities. The 1/3-octave band that would be expected to cause a response at greatest range is considered. Few bowheads would be expected to react at ranges exceeding that where the S:N ratio (industrial noise : ambient noise) is 20 dB. Roughly half would be expected to react at 30 dB. The range where the received level would be 110 dB re 1 µPa is an alternative estimate of the radius of roughly 50% response. Radii of responsiveness for 20 dB and 30 dB S:N criteria assume median ambient conditions.

	A. Stationary Sources			B. Vessels Underway		
					Icebreakers underway	
Site	Bollard Tugs	Drill-ship	Drilling on Sandp.	Tug at Erik	Kigor.	Lemeur
20 dB S:N Criterion**						
Orion	13	(8.8)***	1.8	9.1	14	18*
Sandpiper	23*	(7.5)	1.8	15	13	18*
Hammerhead	34*	6.9	(0.05)	28*	21*	10
Corona	24*	4.6	(0.05)	13	10	7.0
Erik	6.3	4.9	(0.10)	5.2	11	5.6
Belcher	10	7.4	(0.24)	6.3	21	10
30 dB S:N Criterion**						
Orion	4.6	(3.6)	0.19	2.4	7.3	8.3
Sandpiper	7.3	(3.3)	0.19	4.2	8.3	8.3
Hammerhead	11	1.2	(0.02)	7.7	7.9	2.0
Corona	7.2	1.1	(0.02)	3.3	4.6	1.7
Erik	1.5	1.3	(0.02)	1.2	3.0	1.6
Belcher	1.7	1.9	(0.03)	1.1	5.9	2,2
110 dB Abs. Level Criterion						
Orion	6.8	(5.3)	0.29	3.2	9.2	10
Sandpiper	8.3	(4.5)	0.29	5.5	9.7	10
Hammerhead	13	6.9	(0.06)	10	18	7.0
Corona	8.8	3.3	(0.06)	4.4	8.3	4.5
Erik	2.4	5.1	(0.13)	1.6	10	5.7
Belcher	3.8	7.6	(0.29)	1.7	17	7.3

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

**Tabulated values for 20 dB and 30 dB S:N criteria assume median ambient noise conditions. Based on these criteria, the radii of responsiveness would be considerably larger on days with low ambient noise, and smaller on days with high ambient noise (see Section 3.4.5). For the 110 dB absolute criterion, ambient noise level does not affect the tabulated values.

***Parentheses indicate that this industrial source is unlikely to be present at a site with water depth similar to that at this site.

Both the "110 dB absolute" criterion and the "30 dB S:N" criterion represent situations when roughly half the bowheads would be expected to respond. A few bowheads that are less sensitive to industrial noise than average would be expected to occur substantially closer to industrial sites. On the other hand, a few of the more sensitive bowheads would be expected to respond when the industrial noise to ambient noise ratio is as low as about 20 dB in the l/3-octave band of highest S:N. For whales east or west of the six sites considered here, the predicted distances where S:N would be 20 dB on an average day ranged from 5 to 34 km in the cases of the icebreakers underway and tugs, with more variability among sites than among vessels (Table 25). For the drillship, the 20 dB S:N values ranged from 4.6 to 8.8 km, and for the artificial island with drilling the values were 0.05 to 1.8 km.

Regardless of the criterion chosen, the icebreakers underway and/or the tugboats had the greatest potential zones of responsiveness of the six sources considered here. The potential zones of responsiveness around the drillship were generally smaller. The low frequency (40 Hz) sounds from drilling on an artificial island resulted in the smallest potential radii of responsiveness.

The types of industrial activities considered in this section include some of the most important activities at offshore industrial sites, but two significant classes of industrial sources have not been considered here. Some intermittent sources, e.g., an icebreaker pushing or breaking ice, have higher source levels at certain times than do any of the six sources considered above (Table 12). It is not certain whether the criteria' of responsiveness considered here also apply to the peak noise levels from icebreaking. If so, the zone of responsiveness around an icebreaking operation could be considerably larger than the zones around the sources considered here (see Sec. 3.6). The radii of responsiveness to rapidly and directly appreaching vessels are also expected to be larger than those calculated above for vessels underway on tangential courses (see Sec. 3.5).

3.4.4 Zones of responsiveness for gray whales*

General Considerations

The procedures for prediction of zones of responsiveness for gray whales near the Beaufort Sea measurement sites utilize the results of acoustic disturbance studies reported by Malme et al. (1984) and Malme et al. (1986a). The 1984 study concerned migrant whales off the California coast and the 1986 study concerned summering and feeding gray whales in the northern Bering Sea near St, Lawrence Island. Both studies used a broadband underwater projector source for playback of selected industrial sounds and a 100 cu. in. (1.65 ℓ) air gun source to generate seismic survey sounds.

The drillship noise stimulus used in these studies was an EXPLORER II signature obtained in the eastern Beaufort Sea by C.R. Greene in 1981 (Greene 1985); it was the same recording as was used by LGL for their drillship playback tests on bowheads (cf. Richardson et al. 1985b,c). The EXPLORER II signatures measured in 1985 and 1986 differed from the earlier one in that some of the spectrum lines have changed frequency and source level. The dominant portion* of the overall 1986 spectrum is comparable in level to the 1981 data but the major spectrum component has shifted from 240 Hz to 63 Hz. The other industrial

*Prepared by C.I. Malme, BBN Laboratories Incorporated.

*The dominant portion of the industrial noise signal is considered to include the 1/3-octave band with the highest sound level and all other 1/3-octave bands having levels-within 10 dB of that maximum.

noise signatures used in the California playback tests were considerably different in spectrum content from the industrial sources measured during the 1985 and 1986 field season.

Data from the study of summering and feeding gray whales in the northern Bering Sea are most relevant to our present interest in the Beaufort Sea. During the Bering Sea study, whale behavior data were obtained by close observation of focal whale groups, recording surfacing-dive and blow information. In addition, tracking of the focal groups was performed using a two-vessel triangulation procedure or a land-based theodolite when weather permitted. The experimental procedure involved location of feeding whales, observation of behavior during a control period with the support vessels present, observation of behavior during an experiment period with the sound stimulus on, and observation of behavior during a post-experiment control period. Generally, several of these sequences were performed each day.

Limited data obtained for drillship playback sequences did not show any consistent pattern of feeding disturbance or avoidance of the sound source for levels up to 110 dB re 1 μPa in the dominant portion of the spectrum. However, some whales were observed to leave the test area during an experiment when levels reached about 119 dB. These results are similar to the results of the playback tests with migrating gray whales which relate the overall level of the dominant portion of an industrial noise stimulus to a probability of avoidance (Pa) of the area near the source. The data obtained support Pa values ranging from .1 to .9 for the overall effective stimulus bandwidth. It was not feasible to determine which portions of the industrial noise spectra resulted in behavioral response of gray whales. The results are, therefore, specific to the types of sources simulated but are" not site-specific since avoidance was related to sound exposure level rather than to distance from the source.

The procedure used in estimating the zones of responsiveness for gray whales near the Beaufort Sea test sites will therefore use the EXPLORER II signature combined with measured and estimated TL values to predict the ranges at which a Pa of .1 or greater' is expected for feeding gray whales.

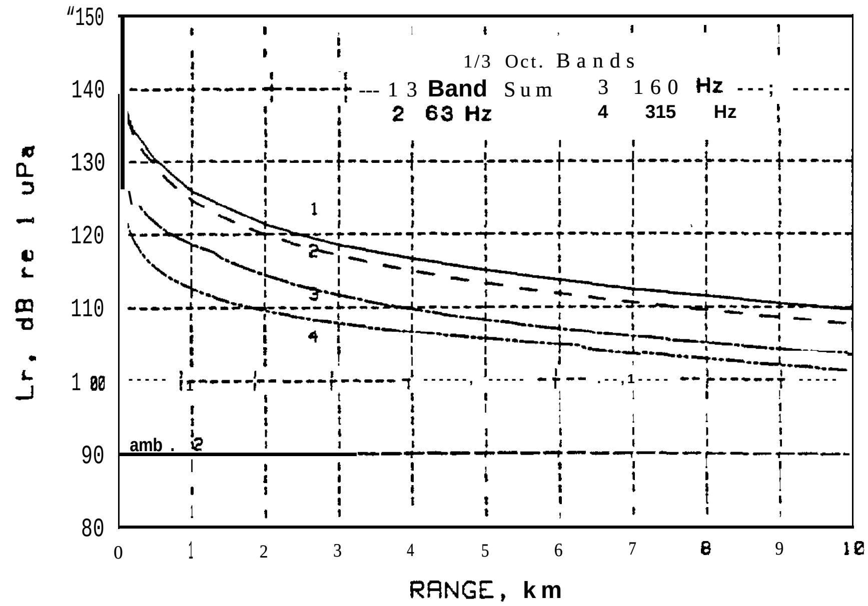
The zone of responsiveness predictions for bowhead whales discussed in the previous section considered three response criteria: two ratios of industrial to ambient noise--2O and 30 dB--110 dB absolute received level. For each of these three criteria, levels and S:N were measured in the l/3-octave band of maximum S:N. It was not possible to determine whether bowheads react to a specific signal-to-noise ratio or to an absolute received level.

In the gray whale playback tests, a Pa value of 0.5 was found when the average ratio of industrial-to-ambient noise was about 20 dB for the dominant part of the drillship playback noise spectrum (typically several l/3-octave bands). The variation in ambient noise level during the California test period was not very large. The observation data were, therefore, not adequate to distinguish whether gray whale response was more clearly related to S:N ratio or to absolute level. Thus, an independent comparison of these two types of acoustic response measures is presently not possible for either species. In the following analysis both measures of potential acoustic response--absolute level and S:N--are considered. The absolute received level procedure differs slightly from that applied for bowheads, in that here the dominant frequency band is considered, which generally included more than one l/3-octave band.

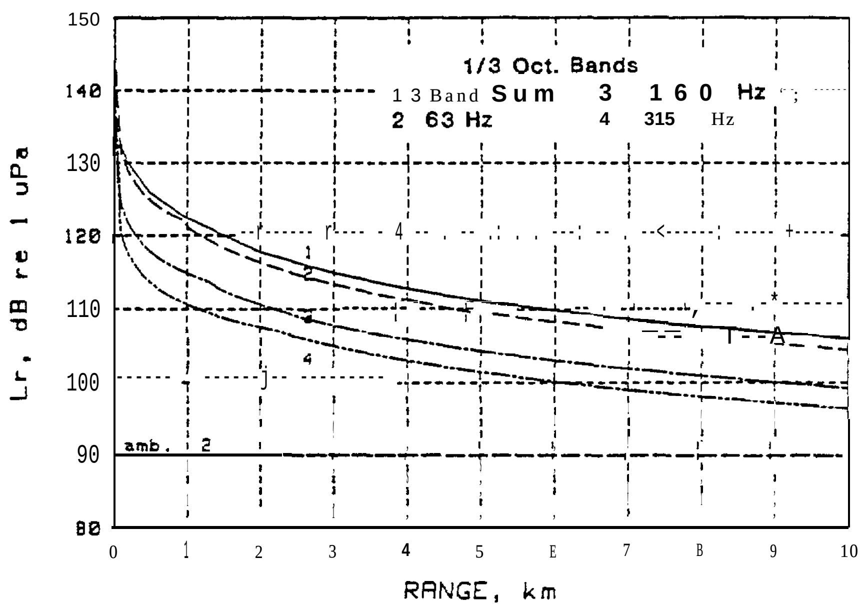
Zones of Resposiveness Estimates

The TL characteristics for the six Beaufort sites were used to estimate the received level versus range for operation of the EXPLORER II drillship at each of the sites. This was done by subtracting the site-specific transmission loss from the source level measured for operation of the drillship at Corona in 1986. The resulting received level curves are shown in Figs. 58A through Fig. 58F. The received level characteristic for each of the three dominant 1/3-octave bands in the 1986 signature was calculated in the same way as for bowheads (Appendix D); in addition, for gray whales the root-mean-square sum of the levels in these three bands was determined. Note that the frequency and range dependence of the TL at the different sites causes an interchange in dominance among the three bands. The received level (Lr) characteristics for the combined bands were compared with the sound levels associated with Pa values of 0.1 and 0.5 from the playback tests described earlier. The corresponding ranges east or west from the drillship were estimated for each of the six sites although it is improbable that a drillship would operate at the shallow sites (Orion and Sandpiper). The results of this procedure are shown in Table 10. In following this procedure we have assumed that the change in the drillship spectrum between that used for the playback tests and that measured in 1986 will not significantly change the degree of response of gray whales to this signal for exposure to the same noise levels.

To provide a direct comparison with the zone of responsiveness results for bowhead whales, the range estimates for 20 and 30 dB S:N ratios are also given in Table 26 for the 1/3 octave band with the highest S:N ratio. The estimated median ambient noise levels for the corresponding sites were used. The specific 1/3-octave noise levels used in these zone of responsiveness estimates are shown in Figs. 58A through 58F.

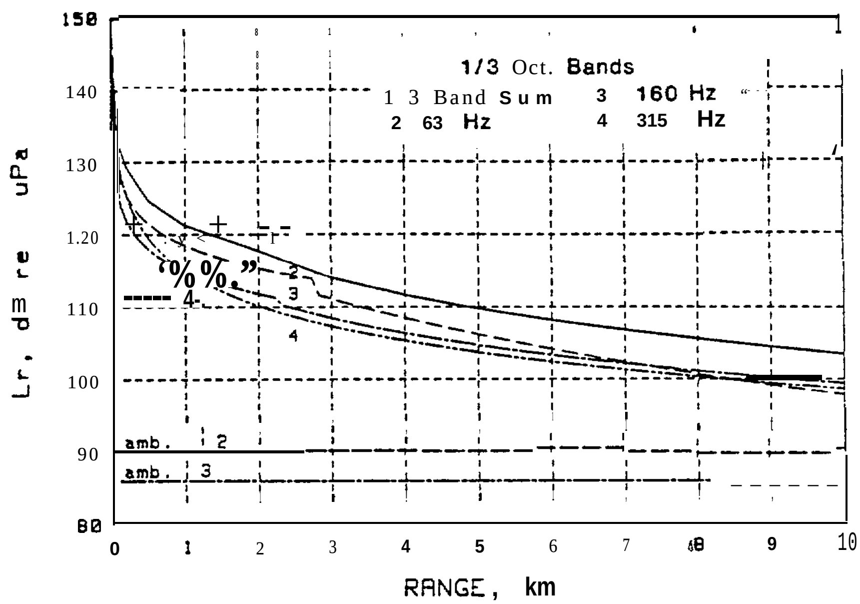


A. EXPLORER II (1986) AT BELCHER

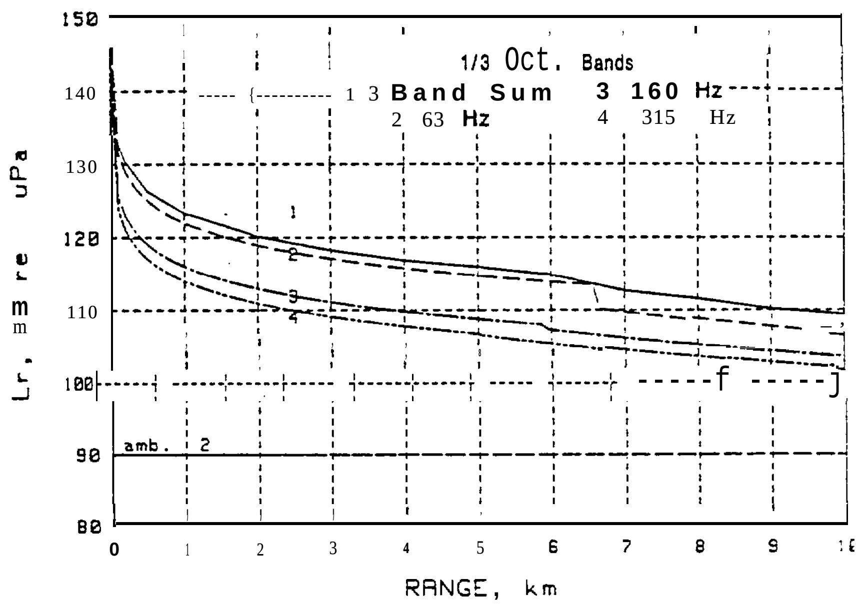


B. EXPLORER II AT ERIK

FIG. 58. ESTIMATED RECEIVED LEVEL CHARACTERISTICS FOR EXPLORER II (1986) OPERATING AT BEAUFORT SITES. AMBIENT NOISE DATA FOR CORRESPONDING SITES AND BANDS ARE FROM SECTION 3.1. EAST/WEST PROPAGATION IS ASSUMED.

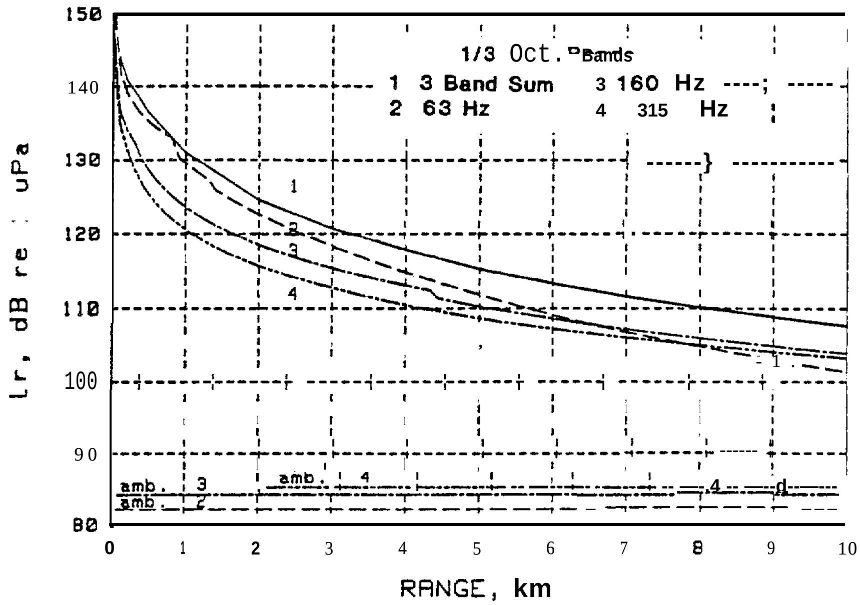


C. EXPLORER II AT CORONA

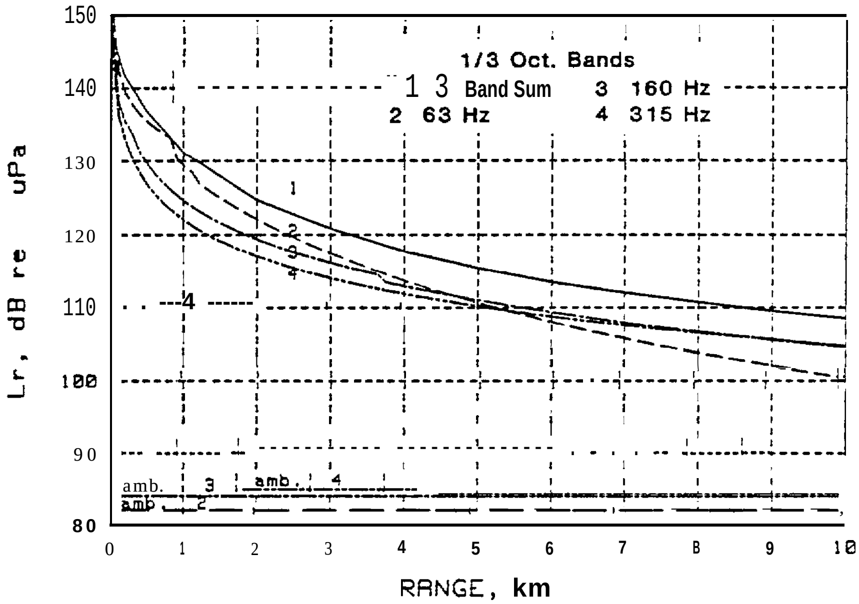


D. EXPLORER II AT HAMMERHEAD

FIG. 58. (CONT.) ESTIMATED RECEIVED LEVEL CHARACTERISTICS FOR EXPLORER II (1986) OPERATING AT BEAUFORT SITES. AMBIENT NOISE DATA FOR CORRESPONDING SITES AND BANDS ARE FROM SECTION 3.1. EAST/WEST PROPAGATION IS ASSUMED.



E. EXPLORER 11 AT SANDPIPER



F. EXPLORER II AT ORION

FIG. 58. (CONT.) ESTIMATED RECEIVED LEVEL CHARACTERISTICS FOR EXPLORER II (1986) OPERATING AT BEAUFORT SITES. AMBIENT NOISE DATA FOR CORRESPONDING SITES AND BANDS ARE FROM SECTION 3.1. EAST/WEST PROPAGATION IS ASSUMED.

TABLE 26. ZONES OF RESPONSIVENESS EAST OR **WEST** OF BEAUFORT SITES FOR GRAY WHALES BASED ON OBSERVATIONS OF FEEDING DISTURBANCE AND AVOIDANCE RESPONSE FOR DRILLSHIP NOISE PLAYBACK (MALME ET AL. 1986a).

	Est. Range From Source Where 1/3 OB with Highest S:N Exceeds Median by:[2]		**Est. Range From Source Where L_r (dB re 1 µPa) is:**[1]	
			$(P_a = 0.1)$	$(P_a = 0.5)$
	20 dB	30 dB	110 dB	120 dB
Belcher (55 m)	7.4 km	1.9 km	9.6 km	2.4 km
Erik (40 m)	4.9	1.3	5.9	1.4
Corona (35 m)	4.6	1.1	4.8	1.4
Hammerhead (30 m)	6.9	1.2	9.1	2.1
Sandpiper[3] (15 m)	(9.3)3	(4.9)	(8.1)	(3.3)
Orion[3] (14 m)	(9.2)	(4.5)	(8.6)	(3.3)

Notes: 1. The effective source level is estimated to be 169 dB re 1 µPa at 1 m as determined by a power sum of the source levels in the dominant 63, 160, and 315 Hz, 1/3-octave bands. Range estimates are for sound transmission east or west of sites.

2. See Fig. 55 for highest band at the stated range; for the four deepest sites, estimates are the same as those calculated for bowheads (Table 24).

3. The drillship probably would not be used at these shallow sites but the range estimates have been included for general comparison purposes, hence the parenthetical entries.

The 'estimated radius of responsiveness values for a 0.1 probability of feeding disturbance, based on the $L_r = 110$ dB criterion, are 4.8 to 9.6 km depending on site. These values correspond to radii where the S:N ratio in the highest 1/3-octave band would be about 17 to 22 dB for most sites. For a 0.5 probability of feeding disturbance and avoidance ($L_r = 120$ dB) the radii would be 1.4 to 3.3 km. These values correspond to S:N ratios of 27 to 35 dB.

The predicted radius of 50% responsiveness (120 dB criterion) varies considerably from site-to-site as shown in Table 26. The smallest zone is predicted for the Erik and Corona sites with a 1.4 km radius. This can be compared with the 3.3 to 5.1 km radii predicted for roughly 50% response by bowhead whales at these sites (110 dB criterion; Table 25). The largest zone of responsiveness for gray whales to drillship noise is predicted for the Sandpiper and Orion sites, with a 3.3 km radius.

These zones of responsiveness have been predicted for conditions of neutral or small SVP gradients. For conditions expected to exist during the early and late parts of the bowhead migration the zone estimates should be modified using TL corrections based on measured or estimated changes in the SVP conditions at each site. This procedure is described in Appendix C.

3.4.5 Variations in zones of responsiveness*

Effect of Variable Ambient Noise -- For bowheads, two of our three criteria for zone of responsiveness are based on the signal-to-noise (S:N) ratio for industrial sounds (signal) relative to natural ambient noise. As indicated in Section 3.1, temporal variations in ambient noise level occur naturally as a result of variable wind, wave and ice conditions, precipitation,

*By W.J. Richardson, LGL Ltd., and C.I. Malme, BBN Laboratories Incorporated.

and other factors. These variations can be quite large. Hence, the radius where S:N for industrial noise is 20 dB or 30 dB--two of our criteria for defining the zone of responsiveness--can also vary widely. Zones of responsiveness estimated by the third criterion, the 110 dB absolute received level criterion, are unaffected by variations in ambient noise.

Most of the estimates of zones of responsiveness presented in Section 3.4.3 involved median ambient noise conditions. However, the effects of variable ambient noise on zones of responsiveness at a shallow (14 m) site, Orion, were summarized briefly. In this section, the effects of variable ambient noise on estimated zones of responsiveness are estimated in more detail for a deeper (35 m) site, Corona. Figure 59 shows received levels of industrial noise as a function of range for the dominant l/3-octave band, along with the 5th, 50th and 95th percentile ambient noise levels in the corresponding band. The estimates are based on the same Weston/Smith propagation models as discussed in previous sections. Figure 59 shows most of the same calculated results as Fig. 55, but plots them against a logarithmic distance scale. This facilitates reading the ranges where S:N is 20 or 30 dB above the three selected ambient noise levels. Table 27 summarizes the results for propagation east or west from Corona.

At Corona, the estimated radius of responsiveness around most industrial activities was estimated to be several times as large under quiet 5th percentile ambient noise conditions as under the previously discussed (Section 3.4.3) median ambient conditions (Table 27). Similarly, the estimated radius was several times as large under median conditions as under noisy 95th percentile conditions. For example, based on the 20 dB S:N criterion, the zone of responsiveness around the drillship was estimated to be 0.81 km under 95th percentile ambient noise conditions, 4.6 km under median conditions, and 28 km under 5th

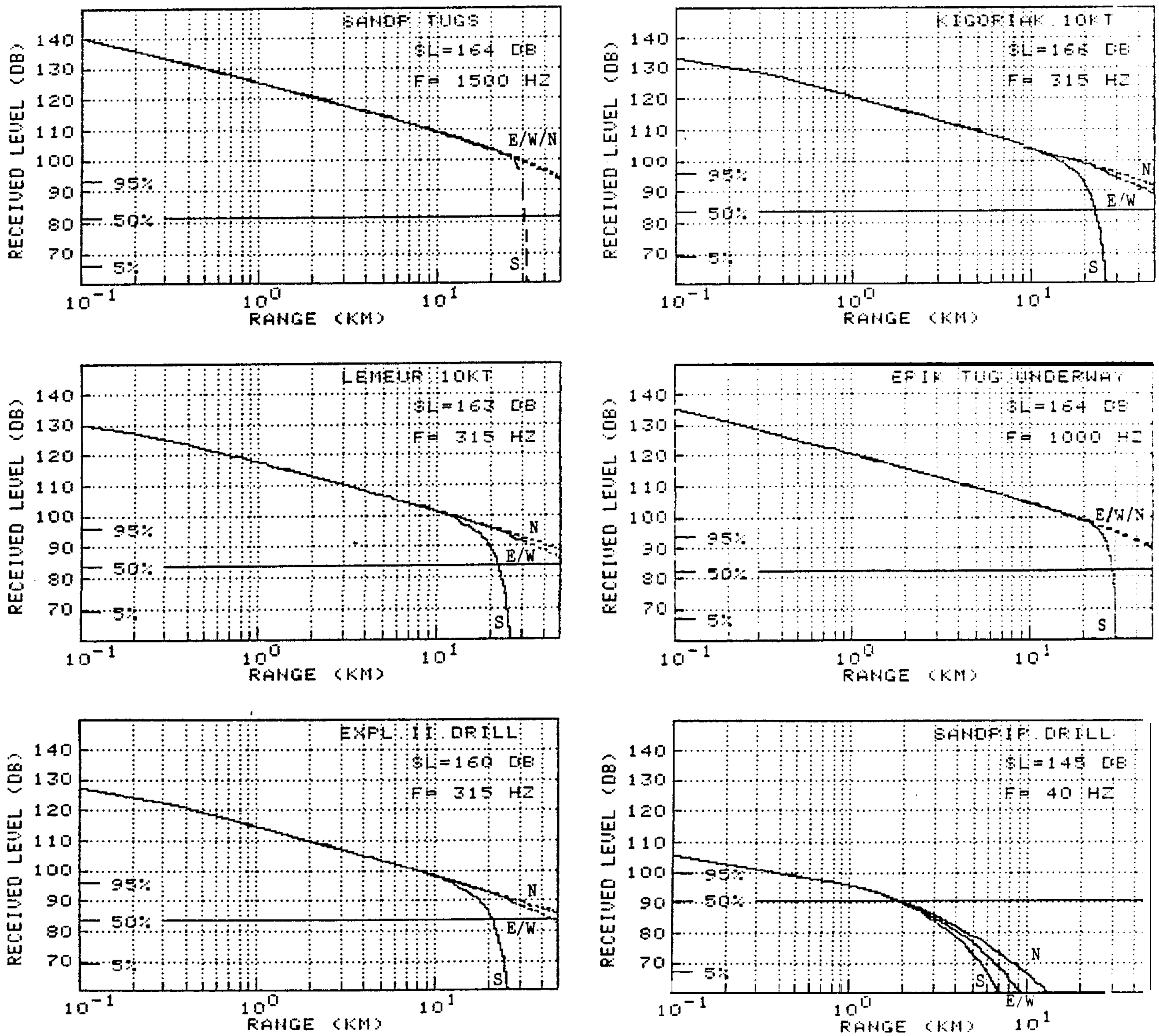


FIG. 59. ESTIMATED RECEIVED LEVELS AND SIGNAL-TO-AMBIENT NOISE RATIOS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE CORONA SITE IF EACH OF SIX INDUSTRIAL NOISE SOURCES **WERE** OPERATING THERE. PRESENTATION AS IN FIG. 54, EXCEPT THAT DISTANCE IS PLOTTED ON A LOGARITHMIC SCALE.

Table 27. Effect of ambient noise level on predicted "zones of responsiveness" (in km) for whales east or west of the Corona site if one of six industrial activities was present.

Site	A. Stationary Sources: Bollard Tugs at Sandp.	A. Stationary Sources: Drill-ship	A. Stationary Sources: Drilling on Sandp.	B. Vessels Underway: Tug at Erik	B. Vessels Underway: Icebreaker underway: Kigor.	B. Vessels Underway: Icebreaker underway: Lemeur
20 dB S:N Above						
5 %'ile	>50*	28	(2.6)	>50*	>50*	36*
Median	24*	4.6	(0.05)	13	10	7.0
95 %'ile	5.7	0.81	(0.02)	2.4	4.3	1.2
30 dB S:N Above						
5 %'ile	42*	11	(0.81)	23	18	13
Median	7.2	1.1	(0.02)	3.3	4.6	1.7
95 %'ile	1.4	0.14	(<0.01)	0.60	0.66	0.26
110 dB Absolute Rec'vd Level	8.8	3.3	(0.06)	4.4	8.3	4.5

*Asterisk indicates that calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

Underlining indicates that the calculated zone of responsiveness is based on a frequency other than that shown in Figure 59 (i.e., calculated zone based on another frequency exceeds that shown in Figure 59).

() Parentheses indicate that drilling on an artificial island is unlikely to occur at a site as deep as Corona. -

percentile conditions. Corresponding values based on the 30 dB S:N criterion were 0.14, 1.1 and 11 km (Table 27). For the two tugs in bollard condition, which was the source with the largest calculated radii of responsiveness at this site, the 20 dB S:N values were 5.7, 24 and >50 km, and the 30 dB S:N values were 1.4, 7.2 and 42 km.

These values all refer to propagation east or west from Corona. Results for northward propagation were similar (Fig. 59). Results for southward propagation, especially those based on the 20 dB S:N criterion, would not be quite as strongly dependent on ambient noise, since S:N would decrease more rapidly with increasing distance to the south.

In general, it is apparent that the radius of responsiveness will be strongly dependent on ambient noise level if the appropriate criterion of responsiveness is a specific signal-to-noise ratio. The area of the zone of responsiveness will be even more variable than the radius, since area depends on radius squared. For example, if the radius of responsiveness increases five-fold as a result of a decrease in ambient noise level, the area of the zone of responsiveness will increase 25-fold. Similarly, if the radius decreases five-fold as a result of an increase in ambient noise, the area of responsiveness will decrease 25-fold.

<u>Effect of Variable Transmission Loss</u> -- All previous discussion of zones of audibility and responsiveness has assumed "typical" rates of sound transmission loss with increasing distance from the source. However, transmission loss rates can be more or less than average, depending on water mass characteristics (see Section 3.3). If there is a "sound duct", transmission losses are lower, and the zone of influence can be expected to be larger. If there is downward refraction of sound, transmission losses are higher, and the zone of influence would

be smaller. The magnitude of this variability is expected to be frequency dependent (Section 3.3). Variable propagation conditions have less effect at low frequencies than at moderate and higher frequencies.

To assess the effects of variation in propagation losses on zones of noise influence, we considered northward propagation from two industrial sources that were assumed to be at the Corona site (Fig. 60). The middle line on each diagram is the estimated received level in the dominant l/3-octave band based on the usual Weston/Smith sound propagation model--the same curve as the northward propagation curve in Fig. 59. The lower line shows the lower expected received levels under downward refracting conditions, as derived in Section 3.3. The upper line shows the higher expected received levels under ducting conditions.

Propagation conditions had a considerable effect on the predicted zones of influence when the zone was large, but had much less effect when the zone was small. This was a result of the increasing divergence of the received level curves with increasing distance (Fig. 60). For example, based on the 30 dB S:N criterion, the predicted zone of responsiveness to the north of the drillship was small, only 1.1 km, and the values under the alternate propagation conditions were similar, 0.9 to 1.3 km (Table 28). However, based on the same criterion and considering a noise source for which the estimated radius of responsiveness was larger--a tug underway--, the predicted radius was 3.3 km under typical propagation conditions, but ranged from 2.4 to 8.0 km under poor and good propagation conditions.

The examples quoted above, along with the 20 dB S:N values in Table 28, assume median ambient noise conditions. The range of variability would be considerably greater if variation in both ambient noise and propagation conditions were considered together.

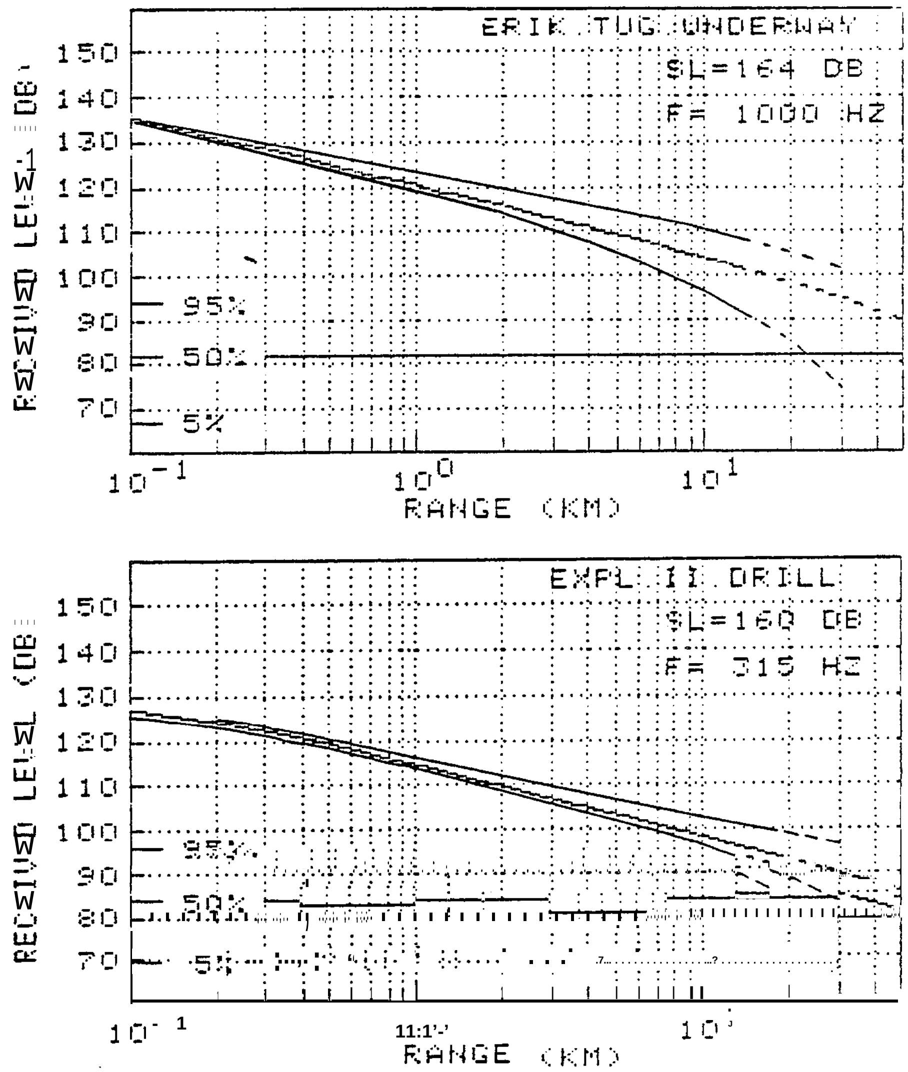


FIG. 60. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES NORTH OF THE CORONA SITE UNDER THREE PROPAGATION CONDITIONS IF EACH OF TWO INDUSTRIAL NOISE SOURCES WERE OPERATING THERE. IN EACH GRAPH, MIDDLE CURVE REPRESENTS TYPICAL PROPAGATION CONDITIONS, UPPER CURVE REPRESENTS SOUND DUCTING CONDITIONS (GOOD PROPAGATION), LOWER CURVE REPRESENTS DOWNWARD REFRACTING CONDITIONS (POOR PROPAGATION).

Table 28. Effect of propagation conditions on predicted "zones of responsiveness" (in km) for whales north of the Corona site if one of two industrial activities was present. Based on sounds in one of the dominant l/3-octave frequency bands, as shown in Fig. 57.

	Tug at Erik	Drill-ship
20 dB S:N Above Median		
Duct	28*	7.2
Typical	13	4.6
Downward Gradient	6.5	3.4
30 dB S:N Above Median		
Duct	8.0	1.3
Typical	3.3	1.1
Downward Gradient	2.4	0.9
110 dB Abs. Rec'vd Lev.		
Duct	10	2.6
Typical	4.4	1.9
Downward Gradient	3.0	1.4

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

Figure 60 can be used to estimate the joint effects of the two sources of variation. For example, considering the drillship and a 20 dB S:N criterion of responsiveness, the predicted radius of response would be only about 0.6 km north of Corona with poor propagation and 95th percentile, ambient noise conditions, and at the other extreme would be >50 km with good propagation and 5th percentile ambient noise conditions (Fig. 60).

Variable propagation conditions affect the zones of responsiveness estimated by absolute received level criteria as well as signal-to-noise ratio criteria. For example, noise from a tug underway at Corona would be expected to diminish to 110 dB at a range of 4.4 km under typical propagation conditions, 3.0 km under poor propagation conditions, and about 10 km under good propagation conditions (Table 28). Variable ambient noise has no effect on the zones calculated with absolute received level criteria. Hence, the combined effects of variable ambient noise and variable propagation are no greater than those of variable propagation alone if an absolute noise level criterion (like 110 dB) is appropriate.

3.4.6 Zone of masking

Masking of whale calls or other environmental sounds by industrial noise is a possibility at distances from the industrial source up to that where the received level of industrial noise has diminished to equal the natural ambient noise. Within that range, sound signals are expected to be masked by industrial noise if the received level of industrial noise exceeds the received level of the sound of interest. Thus, for a receiving whale close to an industrial site, the industrial noise level may be high and the whale will be able to hear only nearby whales whose calls have high received levels. For a receiving whale farther from an industrial site, the industrial noise level will be lower and the whale will be able to hear weaker calls from more distant whales. The same arguments apply to detection of other environmental sounds that may be of interest to whales. Only the industrial noise that is within a l/3-octave band centered at the frequency of the whale call is expected to be relevant (Section 2.3.1).

To provide quantitative estimates of the relationships outlined above, we considered the propagation of industrial sounds and whale calls near the Corona drillsite. Source levels of bowhead calls have been reported to range from 129 to 189 dB re 1 µPa at 1 m (Cummings and Holliday 1985, 1987). Bowhead calls are typically at about 100 to 200 Hz, although some “high” calls are near 600 Hz (Clark and Johnson 1984; Würsig et al. 1985), For these three frequencies, Figure 61 shows the expected received level as a function of source level and distance.

Under median ambient noise conditions without industrial noise, an intense bowhead call with a source level of 180 dB is expected to be detectable about 37 km away if it is at 100 Hz, and >50 km away if it is at 200 or 600 Hz (Fig. 61, Table 29). A weak bowhead call with source level 140 dB would be detectable under median ambient conditions only 2.9 - 7.9 km away, depending on frequency.

Industrial noise sources such as tugboats and icebreakers underway often have source levels of about 170 dB in one or more l/3-octave bands (Table 12). If we consider an industrial activity with source level 170 dB re 1 µPa-m in the l/3-octave band centered at 200 Hz, the expected received level east or west of Corona would be 40 dB above the median ambient figure (85 + 40 dB) at a range of 0.7 km, 30 dB above ambient at 3.3 km, 20 dB above ambient at 12 km, and 10 dB above ambient at 30 dB; it would not diminish below the median ambient level until just over

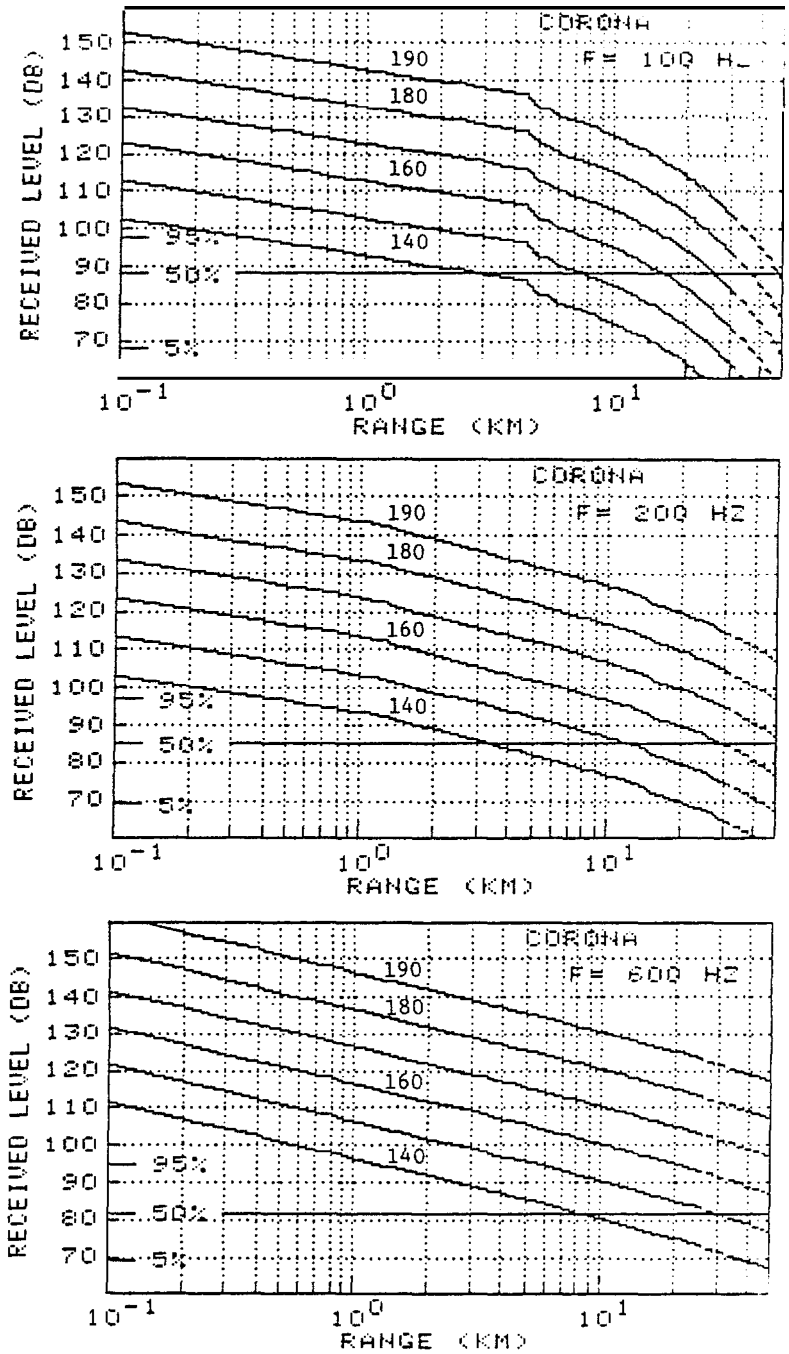


FIG. 61. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE OR WHALE CALLS AS A FUNCTION OF SOURCE LEVEL (140 TO 190 dB) AND DISTANCE FROM SOURCE, ASSUMING EAST OR WEST PROPAGATION FROM THE CORONA SITE. CALCULATIONS WERE DONE WITH WESTON/SMITH PROPAGATION MODELS FOR THREE FREQUENCIES REPRESENTATIVE OF MOST BOWHEAD WHALE CALLS--100, 200 AND 600 HZ. ESTIMATED MEDIAN, 5TH PERCENTILE AND 95TH PERCENTILE AMBIENT NOISE LEVELS (1/3-OCTAVE BAND) ARE ALSO SHOWN.

Table 29. Data for estimating zones of masking around the Corona site for various source levels of industry noise and bowhead calls. This table gives the ranges where various received levels would be found .

1/3-Oct. Band Center Freq.	Received Level & Noise Level (dB re 1 µPa)	Range (km) for Various Rec'vd Levels of Industry Sound or Bowhead Calls					
		SL=140	SL=150	SL=160	SL=170	SL=180	SL=190
100 Hz	88 dB (Median Ambient)	2.9	7.5	16	26	37*	48*
	98 dB (Meal Amb + 10 dB)	0.29	2.9	7.5	16	26	37*
	108 dB (" " + 20 dB)	0.05	0.29	2.9	7.5	16	26
	118 dB (" " + 30 dB)	0.02	0.05	0.29	2.9	7.5	16
	128 dB (" " + 40 dB)	<0.01	0.02	0.05	0.29	2.9	7.5
200 Hz	85 dB (Median Ambient)	3.3	12	30	>50*	>50*	>50*
	95 dB (Meal Amb + 10 dB)	0.68	3.3	12	30	>50*	>50*
	105 dB (" " + 20 dB)	0.07	0.68	3.3	12	30	>50*
	115 dB (" " + 30 dB)	0.02	0.07	0.68	3.3	12	30
	125 dB (" " + 40 dB)	<0.01	0.02	0.07	0.68	3.3	12
600 Hz	82 dB (Median Ambient)	7.9	29*	>50*	>50*	>50*	>50*
	92 dB (Meal Amb + 10 dB)	1.9	7.9	29*	>50*	>50*	>50*
	102 dB (" " + 20 dB)	0.42	1.9	7.9	29*	>50*	>50*
	112 dB (" " + 30 dB)	0.09	0.42	1.9	7.9	29*	>50*
	122 dB (" " + 40 dB)	0.02	0.09	0.42	1.9	7.9	29*

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

50 km away (Fig. 61, Table 29). Thus, any whale less than about 50 km away might experience difficulty in detecting calls from other whales, depending on (1) the distance of the calling whale from the receiving whale, and (2) the source level of the calls:

- A receiving whale >50 km from the industrial source would be able to hear any call whose received level was above the ambient level; there would be no masking. Whale calls with source levels of 180, 160 and 140 dB would be detectable as much as >50 km, 30 km and 3.3 km away, respectively.

  A receiving whale 30 km from the 170 dB industrial source would be exposed to industrial sounds with received level 95 dB, or 10 dB above median ambient. Whale calls with source levels of 180, 160 and 140 dB would be detectable (i.e., would have received levels of at least 95 dB) if the calling whale were as much as >50 km, 12 km, and 0.7 km away from the receiving whale. Thus, there would be some reduction in communication range even for whales as much as 30 km away from the industrial source, but short distance communication would be largely unaffected.

  A receiving whale 12 km from the 170 dB industrial source would be exposed to sounds with received level about 105 dB, or 20 dB above median ambient. Whale calls with source levels of 180, 160 and 140 dB would be detectable if the calling whale were as much as 30, 3.3 or 0.07 km away.

  A receiving whale 3.3 km from the 170 dB industrial source would be exposed to industrial sounds with received level 115 dB, or 30 dB above median ambient. Whale calls with source levels of 180, 160 and 140 dB would be detectable if the calling whale were as much as 12 km, 700 m or 20 m away, respectively.

> A receiving whale 0.7 km from the 170 dB industrial source would be exposed to industrial sounds with received level 125 dB, or 40 dB above median ambient. Whale calls with source levels 180, 160 and 140 dB would be detectable only if the calling whale were within 3.3 km, 70 m or <10 m, respectively.

These values all come from Table 29, and can also be obtained from Figure 61. Those sources can also be used to obtain corresponding estimates for different frequencies or source levels of whale calls and industrial sounds.

It is apparent that whales within several kilometers of typical industrial sources will find it difficult to hear weak calls (e.g., source level 140 dB) from other whales more than a few tens of meters away or, at most, a few hundreds of meters away unless they have a more sophisticated discrimination capability than assumed above. However, strong calls (e.g., source level 180 dB) will be detectable over distances of several kilometers even for a receiving whale within a few kilometers of a typical industrial source. As a rough “rule of thumb”, a whale x km from an industrial site is likely to be able to hear another whale if it is no more than about x km away, based on the fact that strong industrial sounds and strong bowhead calls are generally similar in source level.

Natural ambient noise levels are highly variable, and this leads to great natural variability in the radius of audibility of whale calls. It is not uncommon for ambient noise to be 10 dB above median ambient levels (Section 3.1). A 20 dB increase is also possible under stormy conditions or with moving ice cover. A 10 or 20 dB elevation in ambient noise level is expected to reduce the radius of audibility of whale calls by the same amount as will occur when the received industrial noise level is 10 or

20 dB above median ambient (Fig. 61). Whales must be able to cope with these types of natural increases in noise level, and with the corresponding reductions in communication radius, at least over periods of hours or a few days.

One way in which whales may cope with elevated background noise levels is by adjusting the source levels or frequencies of their calls in order to reduce the masking effect. Some toothed whales apparently do this (Au 1980; Au et al. 1985). It is not known whether baleen whales do so, but it would not be surprising if they did. An increase in source level of a call could greatly increase the radius within which another whale could hear that call. For example, if a receiving whale were 12 km from a 170 dB industrial source, it could hear a calling whale only up to 3.3 km away if the source level of the calls was 160 dB, but 30 km away if the source level was 180 dB {Table 29; 200 Hz).

Another possible way in which the effects of masking may be reduced is through directional hearing. In dolphins, a directional hearing capability has been shown to reduce the masking effect when the masking noise and the sound signal arrive from widely divergent directions (see Fig. 9, from Zaytseva et al. 1975). The above calculations assume that the degree of masking is unaffected by differences in direction of arrival of the masking noise vs. the whale call or other signal of interest. It is probable that baleen whales have directional hearing capabilities even at the low frequencies and in the shallow waters under consideration here. The fact that bowheads and gray whales tend to orient away during some industrial noise playback experiments shows that they have some localization ability. If the whales' auditory systems take advantage of directional hearing abilities, this could considerably reduce the masking effect relative to the "first approximations" discussed above.

In summary, short distance communication, i.e., over distances less than 1 km, is likely to be impaired only for whales that are very close to industrial sites. Furthermore, it is likely that most whales would avoid approaching this close to industrial sites, so short-distance masking would not come into effect. Long distance communication is much more likely to be masked. However, whales must be able to deal with temporary interruptions in their ability to communicate over long distances, since storms and moving ice cause naturally elevated background noise levels. Furthermore, whales are probably able to use countermeasures to reduce masking problems, e.g., by increasing source levels of calls, calling at frequencies where the background noise level is less, and taking advantage of directional hearing capabilities.

3.5 Responses of Bowheads to Direct Approaches by Vessels

Radii of responsiveness were calculated in Section 3.4.3 not only for stationary industrial activities, but also for vessels underway near bowhead whales. The calculations for vessels underway were based on the assumption that the criteria of responsiveness derived for stationary industrial activities also apply to vessels underway. Those criteria assume that roughly half of the bowheads will react when the received noise level in the 1/3-octave band of maximum signal-to-noise ratio is 110 dB re 1 μPa, or 30 dB above ambient, and that a minority will react at a S:N of 20 dB (Section 2.3). We emphasized in Section 3.4.3 that the radii of responsiveness calculated there apply to situations when the noise level received by the whales is more-or-less constant. In the case of a vessel underway, this would occur if the ship were stationary, or moving in a local area distant from the whales, or if it passed the whales in a tangential fashion.

Bowhead whales have been found to react strongly and consistently to vessels that are heading directly toward the whales (Richardson et al. 1985b,c; Thomson and Richardson 1987, p. 475). One would expect, a priori, that whales would perceive an approaching vessel (i.e., noise level increasing) as a greater threat than a vessel that was not approaching. Thus, in Section 3.4.3 we specifically excluded from consideration any vessels that were directly approaching the whales. We expected that the above-mentioned criteria of responsiveness, which were derived for sources of continuous and more-or-less constant noise, may not apply to noise from approaching vessels.

Previous reports have described the reactions of bowhead whales to vessels in terms of distances but not received noise levels. Richardson et al. (1985b,c) found that most bowheads began to swim rapidly away from directly approaching vessels at distances ranging from 1 to 4 km. There were indications that a few bowheads may react at distances exceeding 4 km. There were also a few observations of bowheads that exhibited no apparent avoidance reaction when a boat was passing only a few hundred meters to the side. A few of these observations involved vessels of the types used commonly by the oil industry in the Alaskan Beaufort Sea, viz. a supply ship and a seismic vessel underway (not producing noise impulses]. However, the majority of the data on reactions of bowheads to vessels involved smaller (13-16 m long) diesel-powered boats. The spectral characteristics of the sounds from these boats differed from those of the larger vessels that are more commonly used by the oil industry (Greene 1985). The source levels of the sounds from these two classes of vessels presumably differed as well.

3.5.1 Received noise during LGL's vessel disturbance tests

In order to better understand the sensitivity of bowheads to approaching vessels, it was desirable to estimate the sound levels received by the whales that were observed during the boat disturbance experiments of Richardson et al. (1985b,c). The available data sources were reviewed as part of the present project. Acoustic recordings suitable for determining received levels of boat noise as a function of range were available for one of four disturbance experiments conducted with the 13-m diesel-powered boat SEQUEL. During an experiment on 16 August 1982, LGL used a sonobuoy to record underwater sounds as SEQUEL travelled at 13 km/h (7 knots) away from the sonobuoy and toward bowhead whales. The circumstances of this experiment were described in Richardson (cd., 1983, p 132-142, 257-258). This experiment was done in the deep water (about 128 m) of Herschel Canyon, a part of the Canadian Beaufort Sea between Herschel Island and the Mackenzie Delta.

The sounds received from SEQUEL on 16 August 1982 were processed in the following manner as part of the present project. Levels of boat noise received at the sonobuoy were measurable at various times as the boat travelled from 2 km to 5.8 km away. Eleven samples of these sounds were analyzed by Greeneridge Sciences Inc., following the methods of Greene (1985). For each sample, Greeneridge determined the spectral composition of the sounds, broadband level, and levels in all 1/3 octave bands from 20 to 3150 Hz (e.g., Fig. 62). Ambient sounds recorded on 16 August 1982 just before the start of the boat disturbance experiment were analyzed in the same way.

Then BBN used the SEQUEL noise measurements to develop best-fit Weston/Smith sound propagation models for the received levels of SEQUEL sounds in various l/3-octave bands as a function of

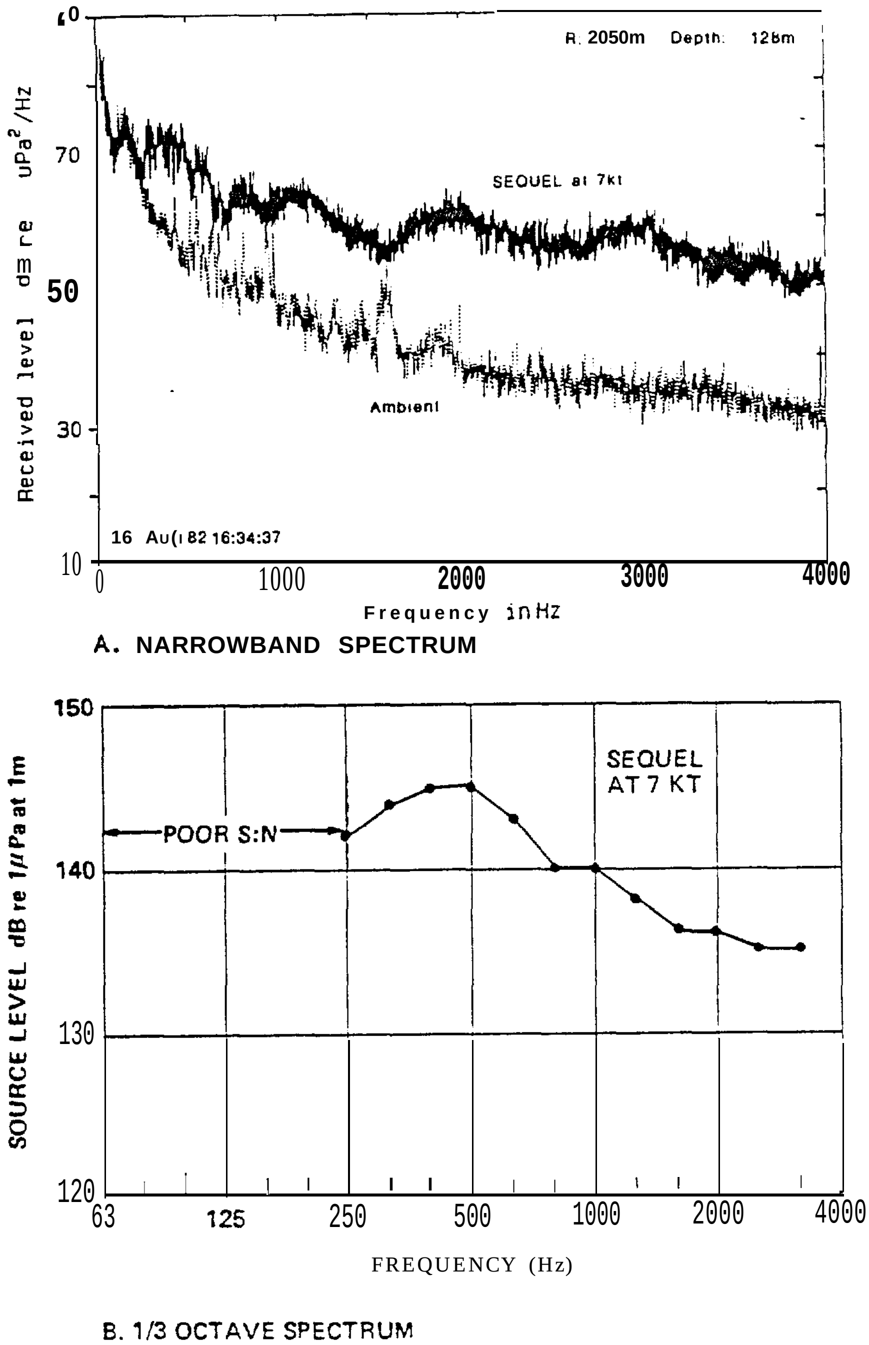


FIG. 62. RADIATED NOISE SPECTRA FOR M.V. SEQUEL MEASURED BY GREENERIDGE SCIENCES NEAR HERSCHEL ISLAND IN THE CANADIAN BEAUFORT SEA, 16 AUGUST 1982.

distance. Received levels at frequencies below 250 Hz were not appreciably above the ambient noise level, so propagation models were derived for 1/3-octave bands from 250 Hz to 3150 Hz. The lack of usable data at frequencies below 250 Hz was not a serious problem because SEQUEL's dominant sounds definitely were above 250 Hz. The propagation models for various bands provided a method for calculating the received level of SEQUEL sound as a function of distance from the boat. Sound levels in the 1/3-octave bands centered at 400, 1250 and 2500 Hz were high relative to ambient levels in the corresponding bands, so those three bands are considered here (Fig. 63A-C).

The following table presents the results of the BBN analysis which used the Weston/Smith sound propagation model to establish the TL characteristics of the test area.

SEQUEL Data Analysis Results*

1/3 Octave Band (Hz)	1/3 O.B. Source Level at 7 kt (dB//μPa at 1 m)	Bottom Loss Parameter (b)	Grazing Angle Parameter ($\sin\phi_C$)
400	145	1.0	0.8
1250	138	1.1	0.8
2500	135	0.8	0.8

*Analyzed for best fit to Weston/Smith Model. Received level data supplied by Greeneridge Sciences, Inc., 10/9/87. Local anomaly (An) assumed to be O dB. Depth = 128 m and bottom slope = 0°.

The measurements of SEQUEL noise were obtained at a deep (128 m) site where one test of the reactions of bowheads to SEQUEL was done. Three additional disturbance tests were done with SEQUEL in water only 6-12 m deep (Richardson et al. 1985c). No direct measurements of SEQUEL noise as a function of distance

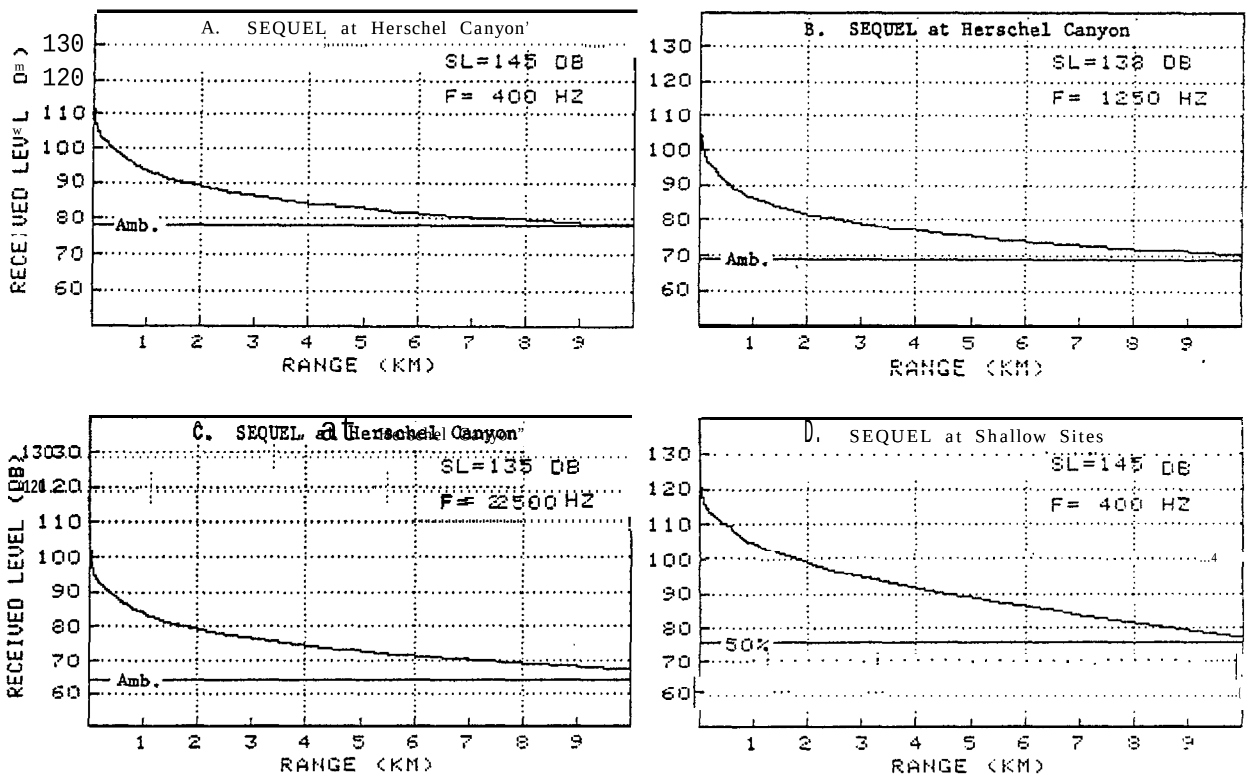


FIG. **63.** ESTIMATED RECEIVED LEVELS OF NOISE FROM THE 13-M BOAT SEQUEL AS A FUNCTION OF DISTANCE. A,B,C SHOW WESTON/SMITH PROPAGATION MODELS FOR SEQUEL IN DEEP WATER, CONSIDERING THREE l/3-OCTAVE BANDS WITH HIGH SOURCE LEVELS. ALSO SHOWN IS THE ACTUAL AMBIENT NOISE LEVEL IN THE CORRESPONDING BANI) NEAR THE TIME OF THE SEQUEL MEASUREMENTS. D SHOWS THE WESTON/SMITH MODEL FOR SEQUEL IN SHALLOW WATER, CONSIDERING THE l/3-OCTAVE BAND CENTERED AT 400 HZ. THE AVERAGE AMBIENT LEVEL FOR THIS BAND IS ALSO SHOWN.

were available for those shallow-water experiments. However, Greene (1985) studied the propagation of other types of industrial sounds in waters near those sites, and BBN developed best-fit Weston/Smith propagation models for some of those measurements (see Table 10 in Section 3.3). Based on those model parameters, an approximate Weston/Smith propagation model was developed for 400 Hz sounds from SEQUEL when the vessel was being used to conduct bowhead disturbance experiments in shallow waters near the Mackenzie Delta (Fig. 63D).

3.5.2 Sensitivity of bowheads to directly approaching vessels

During the 16 August 1982 boat disturbance experiment, bowhead whales as much as 1.5 to 4 km ahead of SEQUEL swam rapidly away from the vessel when it was approaching at 13 km/h (7 kt). A mother and calf were observed swimming rapidly away when the approaching boat was 3.4 km away (Richardson [cd.] 1983; Richardson et al. 1985b). The mother and calf had begun their avoidance reaction at some unknown earlier time when the boat was more than 3.4 km away. Received noise levels and boat noise : ambient noise ratios during this experiment are shown in Figure 63A-C; at ranges 1.5 km and 4 km from SEQUEL, the noise levels were as follows:

1/3 Oct. Band	Absolute RL		Signal:Noise	
Center Freq.	1.5 km	4 km	1.5 km	4 km
400 Hz	91 dB	84 dB	13 dB	6 dB
1250	84	77	15	8
2500	81	74	17	10

Thus, on 16 August 1982 bowheads exhibited strong avoidance reactions when the received noise level in the l/3-octave band of maximum signal to noise ratio was well below the 110 dB absolute level criterion used in Section 3.4.3 for sources of continuous industrial noise. Similarly, strong avoidance occurred when the boat noise : ambient noise ratio in the band of maximum S:N was well below the 20 and 30 dB S:N criteria used in Section 3.4.3.

Similarly, during the three experiments when SEQUEL approached bowheads in shallow water, strong avoidance reactions were observed at distances of 2-4 km (Richardson et al. 1985b,c). The received noise level in the 1/3-octave band near 400 Hz was about 99-92 dB at these distances (Fig. 63D). Again, these values are well below the 110 dB criterion of responsiveness to continuous sounds assumed in Section 3.4.3. Actual ambient noise levels are not known on these three occasions, but the average ambient noise level in the 400 Hz band was about 76 dB (Greene in press) . If actual levels during the three experiments in shallow water were about 76 dB, whales consistently exhibited strong avoidance reactions to an approaching boat when the signal-to-noise ratio was 16-23 dB, less than the 30 dB value at which roughly half of the bowheads apparently respond to continuous noise.

These boat disturbance experiments show that the criteria of responsiveness developed for more-or-less constant noise (Section 2.3 and 3.4.3) do not apply to vessels that are traveling directly toward bowhead whales. Bowheads apparently are more sensitive to noise from approaching boats; they react at lower absolute received levels and lower signal to noise ratios. This is not surprising. Several authors have stated that baleen whales are very sensitive to changing sound levels, and especially to the rapidly increasing sound levels from approaching boats (see Richardson et al. 1983 for review). Thus, bowhead whales would be expected to react to directly approaching vessels at greater distances than were calculated in Section 3.4.3 for more-or-less continuous noise.

The results from the SEQUEL experiments provide an indication of the received noise levels and signal to noise ratios at which most bowheads react to approaching vessels. However, this information probably should not be applied directly to larger ships; the reactions may not be directly comparable:

1. The spectral characteristics of the sounds from SEQUEL are quite different than those from larger vessels like supply ships, icebreakers or large tugboats. The peak noise output from SEQUEL is at higher frequencies than is the peak output from larger vessels (Greene 1985; this study). SEQUEL peak source level at 7 kt is 145 dB//μPa at 1 m in the 400 Hz and 500 Hz 1/3 octave bands while icebreaker KIGORIAK, for instance, in open water at 10 kt is 173 dB//μPa at 1 m in the 63 and 100 Hz bands (Fig. 62 and Table 7).
2. The rate of change of sound level when SEQUEL was 2-4 km away would not be the same as the rate of change expected at a corresponding received sound level from a larger vessel. Received levels increase faster when an approaching vessel is close than when it is far away (e.g., Fig. 63). A given received level (say 90 dB re 1 μPa) would be found at a greater distance from a large vessel than from SEQUEL. Thus the rate of increase when the received level is 90 db would be lower for a large vessel than occurred during the SEQUEL experiments.

The available data indicate that reactions of bowheads to approaching vessels are likely to occur at lower received noise levels and at greater distances than those calculated in Section 3.4.3 for more-or-less continuous noise. However, it is not feasible to provide precise estimates of radii of reponsiveness ahead of approaching ships.

3.6 Responses to Intermittent Noise Sources*

Three industrial activities that produced sounds intermittently, or at variable source levels, were studied in this project. These sources were the icebreaking supply ship ROBERT LEMEUR pushing on ice, a clamshell dredge producing maximum noise levels as the clamshell was raised, and the tugboat ARCTIC FOX during the periods when it was towing a barge (Section 3.2). Radii of audibility for these peak levels were calculated and given in Section 3.4.2. However, we did not attempt to estimate radii of responsiveness in Section 3.4.3 because it is not certain that the criteria of responsiveness used there for more-or-less continuous sources also apply to intermittent sources. Based on prior studies [Malme et al. 1984, Ljungblad et al. (1985b) and Richardson et al. (1985 b,c)] regarding whale responsiveness to the impulsive sounds from seismic survey activities, we have some basis for believing that bowheads and gray whales respond to an average of the intermittent or variable sound energy emanating from a source. However, with the exception of the seismic survey impulse case, we do not have quantitative evidence for this opinion. Nevertheless, it is important to present here a discussion of the potential implications of a major Alaskan Beaufort category of sound source (intermittent rather than continuous) on whale responsiveness.

In this section, we indicate the potential sizes of the zones of responsiveness around these three intermittent sources assuming the possibility that an adjusted source level should be used, taking into account the proportion of the time during which the industrial source is emitting sounds at the peak level. We also discuss the possibility that the whales respond to the peak

*By C.I. Malme, BBN Laboratories Incorporated and W.J. Richardson, LGL Ltd.

levels in the fluctuating signal as they have been observed to do for continuous noise (see Section 3.4.3).

3.6.1 Zone of responsiveness estimates considering equivalent source levels

In humans, it has been found that the annoyance caused by variable sounds such as vehicle traffic, aircraft noise, etc., and other industrial sources is related to the average acoustic energy of the sounds. Humans generally consider these types of variable sounds to be annoying but not threatening; variable sounds from some types of distant industrial operations may have similar characteristics insofar as whales are concerned. The following is a discussion of possible methods of handling this type of source in the context of potential behavioral response of endangered whales.

The acoustic output level and spectrum characteristics of industrial noise sources may vary during a normal duty cycle as a result of changes in operating conditions. Output level fluctuations are particularly of concern for this study since the relationship between sound level and exposure duration in producing behavioral effects in non-human species is not well known. Some guidance can be obtained by review of studies of human annoyance reactions to time-varying industrial noise exposure.

To aid this review, relevant procedures and terminology used in the study of human response to fluctuating industrial noise sources are given below:

<u>Exposure period</u> - A reference period of time for calculating a behavioral response measure such as the equivalent sound level - one of the metrics used to predict annoyance (this

period is generally considered to be 8 hours for human response studies).

Source temporal characteristics-

Steady continuous source - A source with output level varying less than ±2.5 dB during an exposure period.

Fluctuating continuous source - A source with output level varying more than ±2.5 dB but not going below the ambient noise level during an exposure period.

Intermittent source - A source with more than one operating cycle during an exposure period.

Intermittent impulsive source - A source with more than one operating cycle during an exposure period where the output duration is less than 0.1 sec.

Equivalent sound level (L_{eq}) - The level of a continuous source that provides the same acoustic energy as a fluctuating or intermittent source for the same exposure period. The value of L_{eq} may be determined by a continuous integration of the energy output of the time-varying source using the following relationship:

$$L_{eq} = 10 \log \frac{1}{T_p} \int_0^{T_p} \left(\frac{p_r(t)}{P_0}\right)^2 dt \text{ (dB)} \tag{1}$$

where T_p is the time duration of the exposure period

$p_r(t)$ is the time-varying sound pressure in a specified bandwidth

P_0 is a reference sound pressure (1 μPa)

It is often more convenient to do a statistical analysis using discrete logarithmic step increments instead of a continuous integration of the pressure' signal. Steps with 5 dB intervals are recommended in Standard ISO/R 1996-1971

(Assessment of Noise With Respect to Community Response). The procedure is based on the following equation:

$$L_{eq} = 10 \log\left[\frac{1}{100}\sum T_i 10^{L_i/10}\right] \text{(dB)} \tag{2}$$

where T_i is the time interval (expressed as a percentage of the exposure-period) for which the sound level is within the limits of class i (L_i ± 2.5 dB).

L_i is the sound level in a selected band corresponding to the midpoint of the class i.

<u>Duty-cycle</u> - The ratio of the total operating time in an exposure period to the length of the exposure period for a specific source. If an intermittent source produces identical output sequences during an exposure period, Eqn B may be simplified as follows:

$$L_{eq} = L_{eqs} + 10 \text{ Log}(nT_s/T_p) \text{ (dB)} \tag{3}$$

where L_{eqs} is the equivalent sound level of a single output sequence

n is the number of sequences in an exposure period

T_s is the time duration of a single sequence

T_p is the time duration of the exposure period.

If a time-varying source produces most of its output within 5 dB of the maximum level, even though its output sequences are not identical, Eqn. C may be simplified to the form:

$$L_{eq} = L_m + 10 \text{ Log } (T_m/T_p) \tag{4}$$

where L_m is the median level of the highest exposure class

T_m is the total time during which the exposure level **was** within ±2.5 dB of L_m during the exposure period.

(Note that for this case the duty-cycle ≈ T_m/T_p.)

At least some of the characteristics of marine mammal hearing are similar to human hearing with appropriate scaling in frequency ranges and sensitivity values (see Fig. 9). Studies of human reactions to noise exposure show that the degree of annoyance is related to the total energy of the sound exposure (Fidell et al. 1970; Fields and Powell 1987). Thus a doubling of the sound energy level, which requires a 3 dB increase in the equivalent pressure level, produces the about the same increase in annoyance as a doubling of the exposure duration for a constant equivalent pressure level. That is, annoyance relates to 10 log exposure duration. The equivalent sound level as defined above is therefore a convenient measure for estimating the annoyance potential of time-varying sound levels. However, for very short impulses of sound, less than about 0.1 sec in duration, the sensitivity to increases in sound level appears to diminish so that a 5 dB increase in equivalent sound level is required to produce the same annoyance as a doubling of the sound duration for a constant equivalent sound level. These characteristics are shown in the data reported for tests with human subjects by Fidell et al. (1970), see Fig. 64.

Most of the studies of whale response to industrial noise have used only two types of stimuli, playback of source signals with a steady level or with only small fluctuations, and air gun impulses having high peak pressures and short durations. Only a few studies have reported results from tests with intermittent or fluctuating signals. Malme et al. (1984) reported observations of migrating gray whale response to playback of helicopter flyover noise; that same study also included observations of gray

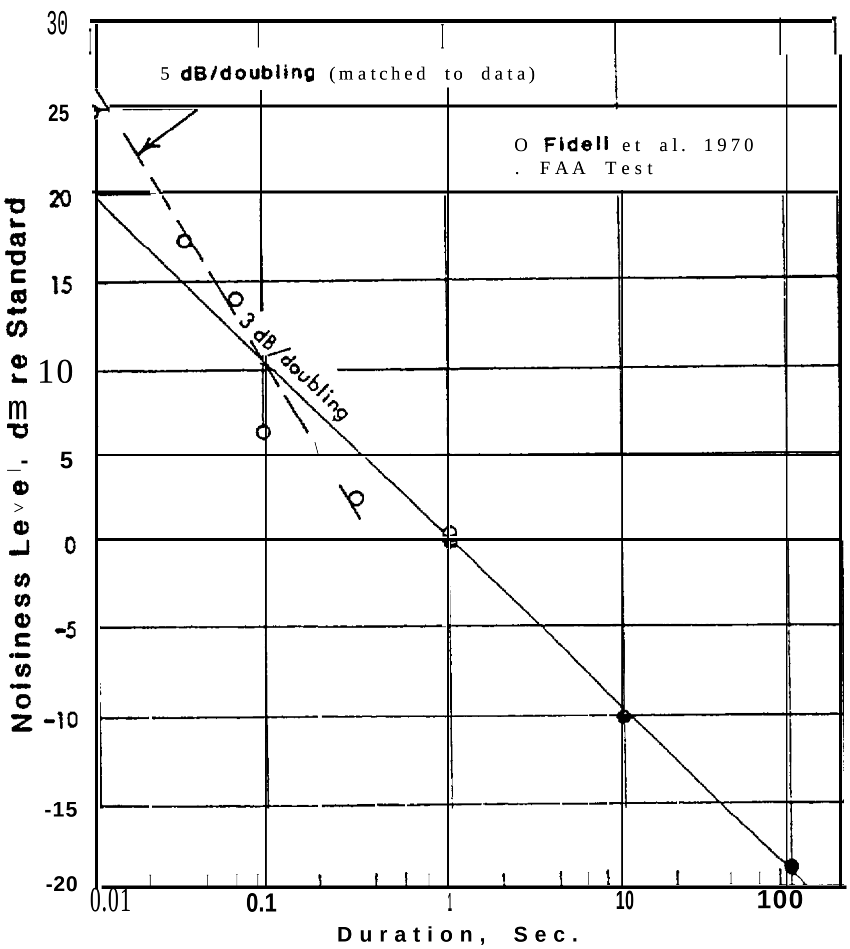


FIG. 64. RESULTS OF TESTS OF NOISE PULSE DURATION VERSUS APPARENT NOISINESS. OCTAVE BANDS OF NOISE OF VARIOUS DURATIONS JUDGED EQUALLY NOISY TO STANDARD 1-SEC OCTAVE BAND OF NOISE. AFTER FIDELL ET AL. (1970).

whale response to air gun impulses. A study of the behavioral response of bowhead whales to increasing levels of boat noise was made by Richardson et al. (1985c) and is reported in detail in Section 3.5. The behavioral reactions of bowhead whales to air gun impulsive noise were studied by Ljungblad et al. (1985b) and Richardson et al. (1985b,c).

The study of the response of gray whales to helicopter noise gave results in terms of the probability of avoidance (Pa) as a function of maximum exposure level. The helicopter noise playback was presented as a series of random flyover sequences with an average repetition rate of l/rein. The effective duty cycle correction based on an analysis of the pressure-time envelope was -11 dB. Comparison of the results for intermittent helicopter noise playback with the results for drillship noise playback, a steady continuous sound, showed that Pa = 0.5 occurred at a maximum exposure level of 120 dB (re 1 μPa for the helicopter sound and at a continuous exposure level of 117 dB for the drillship sound. based on the -11 dB correction factor, an L_{eq} of 117 dB forthe helicopter sound would correspond to a maximum level of 128 dB rather than the value of 120 dB obtained from the data. However, this result must be considered together with results reported for other continuous stimuli used in the same study. For example, the playback noise exposure level reported for Pa = 0.5 for semi-submersible noise was also 120 dB. The difference in exposure level between drillship and semi-submersible continuous sounds for Pa = 0.5 is either the result of experimental variance or the result of whale sensitivity to differences in source spectra. Therefore, comparison of responses to intermittent helicopter flyover noise with responses to steady drillship noise does not provide a clearly defined test of the equivalent energy hypothesis as applied to gray whale response. More detailed testing is needed using the same source in both continuous and intermittent modes to separate temporal effects from spectrum effects in behavioral response observations.

The hypothesis can be tested for impulsive sources using the behavioral response data reported for tests with air gun sources. Malme et al. (1984) reported a Pa = 0.5 for average air gun pulse pressure levels* of 170 dB. These results show that comparable avoidance responses were observed for air gun average pulse pressure levels which were about 50 dB higher than continuous playback sound levels. The air gun pulse duration depended on the distance from the source but was about 10 msec for the test ranges of importance. The repetition period was 10 sec. This results in a duty-cycle of .001. This is a factor of about 2^{-10} so that, if the L_{eq} power law with a 3 dB increase in pressure for each halving of signal duration is used, a correction factor of 30 dB would be needed, resulting in a predicted L_{eq} of 140 - about 20 dB too high. Since the pulse duration is shorter than 0.1 see, it is appropriate to test the 5 dB characteristic indicated by the data shown previously in Fig. 64. This results in a predicted correction factor of 50 dB or an equivalent continuous level of 120 dB for the air gun signal which agrees with the levels of the continuous playback sounds.

The results of this check of behavioral response differences for gray whales for exposures to continuous and impulsive noise sources show that there is a large reduction in sensitivity to industrial noise levels for impulsive sounds. This reduction follows the 5 dB per halving in time duration indicated in human response data for impulsive sounds. These results provide support for the hypothesis that whale response to longer duty-cycle intermittent and fluctuating noise sources may also be

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*The average pulse pressure level was defined as the peak level of an equivalent square-topped pulse having the same acoustic energy and duration as the original pulse.

similar to human annoyance response and may be measurable using a total acoustic energy dose scale. As a result, we have used the equivalent noise level calculation procedure to develop estimates of zones of influence for time-varying industrial sources as in Table 30A and B.

Limited short-term observation and measurement of intermittent sounds radiated from the icebreaker ROBERT LEMEUR pushing ice at Corona, the dredge ARGILOPOTES operating as part of site preparation at Erik and the tug ARCTIC FOX towing a loaded barge away from the dredge resulted in the following duty cycle estimates.

Icebreaker pushing ice:	10% = 0.10
Clamshell dredge working:	14% = 0.14
Tug towing barge:	7% = 0.07

Taking 10 log of these duty cycles yields -10 dB, -9 dB, and -12 dB, respectively, which are then applied to the maximum radiated sound levels measured for each source. The resulting reduced sound levels have then been used in estimating the hypothetical zones of responsiveness to the intermittent sound sources given in Table 30A and B.

In using the equivalent level procedure, we have assumed that the relatively short samples of industrial noise obtained during the monitoring periods at the active industrial sites were representative of operating duty cycles for the sources studied. Determination of the appropriate exposure period for bowhead whales passing near the Beaufort Sea sites is necessary in order to specify the sample duration needed for an adequate characterization of intermittent sources. This period is probably shorter than the 8 hours used in human response studies, which is related to the normal working and sleeping periods. It is likely related

Table 30. Estimated "zones of responsiveness" for bowhead whales to underwater noise from three sources of intermittent industrial noise if they were at the SANDPIPER and ERIK sites, Alaskan Beaufort Sea. The calculations are done in two ways, assuming that our usual criteria of responsiveness should be applied or (A,B) to peak levels adjusted downward by an amount related to the duty cycle (see text), or (C,D) to the peak noise levels. The loudest 1/3-octave band is considered. These are examples only and should not be used to predict whale avoidance at these sites as either method may either be valid or invalid.

Industrial Source	Dir'n from Site	S:N = 20 dB Freq. (Hz)	S:N = 20 dB MedAmb (dB)	S:N = 20 dB Range (km)	S:N = 30 dB Freq. (Hz)	S:N = 30 dB MedAmb (dB)	S:N = 30 dB Range (km)	RL=110 dB Freq. (Hz)	RL=110 dB Range (km)
A. Intermittent Sources at Sandpiper (levels adjusted by duty cycle)									
ICEBR -10 dB	E/W	4000	77	20*	250	84	8.4	400	12
DREDGE -9 dB	E/W	250	84	3.5	250	84	.94	250	1.7
TUG&BARGE-12 dB	E/W	1000	82	7.2	1000	82	1.8	1000	2.4
B. Intermittent Sources at Erik (levels adjusted by duty cycle)									
ICEBR - 10 dB	E/W	250	85	19	250	85	4.6	250	8.8
DREDGE - 9 dB	E/W	250	85	.84	250	85	.09	250	.24
TUG&BARGE-12 dB	E/W	1000	82	2.2	1000	82	.30	1000	.47
C. Intermittent Sources, Peak Levels, at Sandpiper **									
LEMEUR.ICEBR	E/W	2000	80	42*	4000	77	20*	400	26*
ERIK.DREDGE	E/W	1250	82	9.4	250	84	3.1	250	4.8
ERIK.TUG+BARGE	E/W	1000	82	29*	1000	82	9.3	1000	12
D. Intermittent Sources, Peak Levels, at Erik **									
LEMEUR.ICEBR	E/W	250	85	>50*	250	85	19	250	34
ERIK.DREDGE	E/W	250	85	4.6	250	85	.67	250	1.9
ERIK.TUG+BARGE	E/W	1000	82	12	1000	82	2.9	1000	3.9

*Calculated range exceeds the maximum range at which the propagation model was believed to be reliable.

**See Appendix D for corresponding results from other sites, other bands, and other directions of propagation.

to the time required for the migrating bowheads to pass through the zone of influence of an active site. It is difficult to estimate the best value for the exposure period because the speed of advance of the whales is quite variable and the effective zone of influence is dependent on the strength of the dominant source at the site. Fortunately, the calculation of the value of L_{eq} does not require high accuracy in the determination of the exposure period, T_p. Since the noise level steps have 5 dB increments, this allows a factor of 3.2 error in T_p for a l-step error in the L_{eq} estimate as shown in Eqn. 2. Pending revision following more detailed study, an exposure period of 2 hours will be considered appropriate for bowheads moving past the industrial sites studied. This is based on a median 2 kt (3.6 km/hr) speed of advance and a median track distance within the zones of influence of the various sources of 7 km.

3.6.2 Zone of responsiveness estimates considering peak source levels

Although it is possible that whales react to average or "equivalent" sound levels when levels fluctuate, it is also possible that they react to the peak levels. The results of the helicopter playback experiments near migrating gray whales, summarized above, are more consistent with the peak hypothesis. Whales are generally more sensitive to variable sounds than to continuous sounds (reviewed by Richardson et al. 1983). Section 3.5 shows that bowheads are especially sensitive to the special case of a rapidly increasing level of boat noise. A further reason for considering the peak levels of fluctuating sources is that some such sources may occasionally produce peak level sounds for periods longer than the likely exposure period of a migrating whale, e.g., when an icebreaker pushes against a very large ice pan to deflect its course. In this case, the intermittent source becomes effectively continuous, producing its peak level over a prolonged period. Therefore, the following discussion is presented based on the assumption that bowheads may react to the peak level existing in a time sequence of fluctuating sound levels as they do to continuous sounds.

The peak source levels for the intermittent sources considered in this project were 183 dB re 1 μPa for the icebreaker ROBERT LEMEUR pushing ice, 162 dB for the clamshell dredge, and 170 dB for the tug towing a barge. These values are the source levels in the 1/3-octave bands with strongest measured sounds, which were centered at 100 Hz, 250 Hz and 1000 Hz, respectively (Table 12C). In the case of the tug, it is possible that the source level was higher in some band below 400 Hz, where sound levels were unmeasurable due to seismic survey noise interference. Aside from the qualitatively different impulsive sounds from seismic surveys, the 183 dB figure for the icebreaker is the highest source level considered in this project. It is noteworthy that the source level of the icebreaker in the 1/3-octave band centered at 250 Hz was 182 dB, almost as high as the 183 dB value at 100 Hz. Because 250 Hz sounds propagate better in shallow water than do 100 Hz sounds, the highest received levels at a distance from the icebreaker would actually be at 250 Hz (Appendix D).

If the criteria of responsiveness used in Section 3.4.3 apply to the peak sound levels emitted by these intermittent sources, then zones of responsiveness can be calculated in the same way as in Section 3.4.3. Table 30C,D summarizes the calculations for eastward or westward sound propagation from the three sources if they operated (C) at a shallow site such as Sandpiper, and (D) at a deeper site such as Erik. Results of similar calculations for other important frequencies, for other directions of propagation, and for the other four sites appear in Appendix D.

If the usual behavioral response criteria are applicable to peak sound levels, estimated zones of responsiveness around the dredge and the tug would be similar in size to those around other industrial activities with similar source levels (Table 30C,D vs. Table 25). However, the estimated zones around the icebreaker pushing ice would be considerably greater than those around any of the sources of continuous sounds. This result reflects the fact that the peak source level of the icebreaker pushing ice was greater than that of any source of continuous industrial noise (Table 12). If the usual 30 dB S:N or 110 dB absolute level criteria are applicable to the intermittent peak sounds from the icebreaker, roughly half of the bowheads as much as 19-34 km east or west of Sandpiper and Erik might exhibit avoidance reactions. A minority of the bowheads might react 42 to 50+ km away, based on the 20 dB S:N criterion. These estimates assume "typical" propagation conditions and (in the case of the 20 or 30 dB S:N criteria) median ambient noise conditions. As demonstrated in Section 3.4.5, higher or lower estimates might be appropriate on any given day, depending on water mass characteristics and ambient noise levels.

It is emphasized that these estimates for intermittent sources are theoretical, and many uncertainties exist. The calculations depend on the same assumptions as were involved in estimating zones of responsiveness around sources of continuous noise (Table 6). These calculations also assume that the criteria developed for continuous noise are applicable to the peak noise levels from intermittent sources. One argument in favor of this approach, or some similar approach, is that whales are generally more sensitive to variable sounds than to continuous sounds (see review by Richardson et al. 1983). Given this, one might predict that whales would react at least as far away from an intermittent source as they would if that source were producing continuous sounds at a level equaling the peak level of the variable sounds. A further consideration is that the duty cycle for peak sound output can approach 100% over periods of several hours for some sources, e.g., when an icebreaker applies continuous pressure against a large ice pan, to deflect its course. In this case the intermittent source becomes effectively continuous and peak level equals average or equivalent level.

3.6.3 Summary

Table 30 has been constructed for two conditions or assumptions:

1. assuming that bowheads respond to an average or equivalent sound level in the presence of intermittent changes in sound level, or
2. assuming that bowheads respond to maximum sound levels radiated from the source.

The table demonstrates that, for these two assumptions, the duty cycle-adjusted sound levels yield zones of influence which are lower by about 14 km for the working icebreaker, 0.6 km for the dredge and 2.6 km for the tug when considering the 30 dB S:N criterion with the sources operating at Erik site. These limited estimates emphasize the need for a more detailed field and analytical study of whale response to intermittent sources of underwater sound if a more detailed understanding of bowhead response to intermittent sources of sound is to be derived.

If whales respond to all intermittent or fluctuating sound sources in the same manner as they do to seismic survey sounds and as man (such that response relates to an average sound level over a finite period of time or to an equivalent sound level), it is important that the phenomenon be quantified for bowhead and gray whales. In fact, as discussed above, some evidence indicates that both species of whales apparently respond to equivalent sound pressure level when being exposed to short, high-level impulses of sound from seismic survey operations. Table 30A and B provides zone of influence estimates for bowheads for three intermittent sources which assumes that a simplified 10 log (duty cycle) algorithm applies. This algorithm requires that the radiated sound should fluctuate in an “on-off” fashion or have a large swing in sound level, While this is not always the case, its use does provide a rule-of-thumb for estimating the range of influence from the intermittent sources which can be compared to Table 30C and D where maximum ranges of influence for the same sources are shown. Table 30, therefore, provides upper and lower bounds of radii of zones of influence for a working icebreaker, an operating dredge, and a tug towing a loaded barge.

Whichever assumption is correct, the theoretical zone of responsiveness of bowhead whales around a source of strong underwater noise (like an icebreaker pushing “ice) is large. This is especially true if whales are as sensitive to peak noise levels from intermittent sources as they are to corresponding levels of continuous noise. Presently available data are not sufficient to determine whether they are that sensitive to variable and intermittent noise. However, it is noteworthy that two species of toothed whales in the Canadian high arctic, the narwhal Monodon monoceros and the white whale Delphinapterus leucas, have been demonstrated to react to ship and icebreaker noise at very long distances (LGL Ltd. 1986)--consistent with the longest theoretical estimates in Table 30C,D. Of more specific relevance to bowhead whales in Alaskan waters, the reactions of migrating bowheads to various industrial activities were studied by LGL Ltd. and Greeneridge Sciences near the Hammerhead and Corona drillsites in the Alaskan Beaufort Sea in 1986 (work supported by Shell Western et al.). When the results of that study are released, it will be possible to compare some of our theoretical predictions with direct observations of bowhead behavior.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This report presents new underwater acoustic data acquired between mid-August and mid-September 1985 and 1986 at specific offshore drilling sites in the Alaskan Beaufort Sea. It also uses those new data, along with historical data concerning behavioral responses of bowhead and gray whales to acoustic stimuli, to estimate site-specific zones of potential noise influence in the Alaskan Beaufort Sea. Zones of influence associated with selected industrial activities and selected industrial sites have been derived. Emphasis has been given to the bowhead whale, which is by far the more common of the two species of baleen whales observed along the Beaufort coast. Previous studies by LGL have been the primary source of behavioral data used in determining criteria of responsiveness for bowheads. Predictions of zones of influence for gray whales in the Beaufort Sea have been based upon behavioral response research performed by BBN along the coast of California and near St. Lawrence Island in the Bering Sea, taking account of environmental conditions in the Alaskan Beaufort Sea. The BBN gray whale projects were performed under the sponsorship of the Minerals Management Service and were reported in Malme et al. 1983, 1984, 1985, 1986a.

4.1.1 Sites and conditions

MMS specified that environmental acoustic data should be acquired at six offshore oil industry sites (some active and some unoccupied). Each was visited under this project in the years noted.

- Orion site in Harrison Bay, where the Concrete Island Drilling System (CIDS) was operated by Exxon during 1985

- Sandpiper Island, a man-made gravel island near Prudhoe Bay; operated by Shell in 1985 and Amoco early in 1986; visited each year
- Hammerhead, north of Flaxman Island (Unocal), 1986, (some 1985 data were provided by Greeneridge Sciences)
- Corona, north of Camden Bay (Shell), 1985 and 1986
- Erik, north of Barter Island (Amoco), 1985 and 1986
- Belcher, northeast of Barter Island (Amoco), 1985 and 1986.

Heavy sea ice conditions and strong winds occurred frequently during both the 1985 and 1986 measurement periods, resulting in some reduction of the number of acoustic measurements from that planned. Nevertheless, a good sample of drillsite-associated noise was obtained as well as the ambient noise and site-specific acoustic transmission loss data needed for estimating sound levels at potential whale locations.

In 1985, the sources of noise monitored in the 16 August - 19 September time frame of this project were tug and dredge activity at Erik Prospect, pre-drilling preparations at Orion, and stationary tugs at Sandpiper. Greeneridge Sciences provided tape copies of drillship noise recorded at Hammerhead and drill-rig noise recorded at Sandpiper in 1985, which BBN had not been able to measure in 1985. During 1986, BBN recorded drillship noise at Corona, plus noise from icebreaker operations (open water and in ice) at Corona. Seismic survey air gun array impulses were also recorded at Corona and Erik sites.

4.1.2 Acoustic environment

Ambient noise statistics, industrial noise data, and sound transmission loss measurements were acquired and analyzed and the results are presented in Sec. 3. The two-year measurement effort resulted in several important findings.

1. The propagation of underwater sound is unusually efficient over the continental shelf of the Alaskan Beaufort Sea following a cylindrical spreading or 10 log (range R) transmission loss function. This contrasts with the 15 log R or greater loss that is frequently found in similar water depths in more temperate regions. The 10 log R relationship found in this study is consistent with recent results reported for parts of the Canadian Beaufort Sea.

2. It appears that the efficient sound propagation observed at the Alaskan Beaufort Sea sites is associated with the presence of subbottom or subsea permafrost and over-consolidated clay layers, which provide low-loss acoustic reflection surfaces. For low frequency transmission at some shallow sites, the effective depth apparently exceeds the actual water depth, corresponding to reported depths of permafrost and clay layers at some of the sites. Similar subsea permafrost zones have been reported for the Canadian Beaufort continental shelf region.

3. Sound propagation or transmission loss (TL) measurements were obtained to maximum ranges of about 25 km using a controlled sound source and to 40 km for seismic array noise. These data permit confident extrapolation and prediction of drillsite noise transmission to distances of 50 km for some sites.

4. The findings regarding acoustic transmission loss in the Beaufort Sea indicate that migrating and feeding whales

are exposed to higher industrial noise levels at a given distance than would normally be expected in other geographic regions such as the California coast.

5. A “neutral” or relatively invariant sound speed profile can be used to estimate sound propagation characteristics in the Alaskan Beaufort Sea during most summertime periods. However, a strong surface duct for sound propagation was evident in mid-October 1986. It apparently was related to an unusually strong intrusion of warm Bering Sea water at depth near the shelf edge as well as to the normal cooling of surface water prior to freeze-up. The presence of such a duct can cause substantial differences in sound propagation, and as a result, significantly alter the size of the calculated zone of responsiveness for a given ambient noise condition.

6. The noise sources studied under this contract are listed below and are generally ranked in order from the most intense shown first to the least intense. Some variation in the rank-ordering of received sound levels has been shown in Section 3, depending on frequency of the sounds being emitted and the propagation conditions at the particular site under consideration.

   1) Icebreaker pushing ice (heavy propeller cavitation)
   2) Tug(s) working (propeller cavitation)
   3) Icebreaker underway (open water)
   4) Dredge operating
   5) Drillship drilling
   6) Drilling on artificial island.

Vessels underway in open water, tugs forcing a barge against an island (bollard condition), drillship drilling and drilling on an artificial island are considered continuous sources of noise in this study. An icebreaker pushing ice, a tug towing a loaded barge to a dump site, and dredge operations are classified as intermittent or fluctuating sources of sound. The sounds in this second category demonstrate a significant variation in level during, for instance, an expected 2-hour transit period of a whale traveling through the area.

Impulsive noises from seismic survey operations employing an air gun array are the most intense of all industrial noise sources measured in the Alaska OCS region.

4.1.3 Zones of influence

Detailed tables and graphical presentations of the zones of potential detectability and response of endangered whales have been derived for various drillsite noise signatures acquired in 1985 and 1986. Two types of response criteria have been considered, involving (1) various signal-to-noise conditions and (2) various absolute sound levels (Sec. 3.4 and Appendices D, E) . The analysis applied in this research has assumed that either one or both of these two criteria represent the basic causal acoustic measure(s) associated with behavioral response.

Baleen whales are believed to be able to hear industrial noises when the received level of industrial noise equals or exceeds the ambient noise level in one or more l/3-octave bands. Because of the rather high source levels of ships, along with the efficient sound propagation conditions in the Beaufort Sea, most industrial sources are potentially audible, on an average day, as much as 30 to 50+ km east, west, or north of the shallow sites (Orion and Sandpiper), and more than 50 km from the deeper sites (Section 3.4.2). Drilling sounds from an artificial island are one exception; these sounds are not expected to be audible nearly this far away (1.8 to 18 km). All of these estimated radii of audibility are very sensitive to actual ambient noise conditions at the time in question, and to the actual detection sensitivity of the whales (here assumed to be an industrial noise to ambient noise ratio of O dB). Radii of audibility can be much less on a day with above-average ambient noise, and considerably greater on a day with below-average ambient noise.

Expected radii of responsiveness are considerably smaller than radii of audibility. Whales typically do not react overtly to faint industrial sounds even though they may be audible. Generally, previous research on behavioral response of bowhead whales (studied by LGL) has demonstrated that a 30 dB industrial noise-to-ambient noise ratio (S:N) or a 110 dB absolute noise level elicits avoidance responses as well as changes in such variables as swimming speed, breathing rate, and dive times in roughly half of the whales being exposed. A 20 dB signal-to-noise ratio results in less consistent and less conspicuous avoidance responses and other changes in behavior, with a minority of the individual whales reacting overtly and a majority not doing so. These sound levels and S:N ratios represent levels in the l/3-octave band with maximum S:N ratio, and apply to sources of more-or-less continuous noise. Three brief summary tables for bowhead response are repeated here as Tables 31 through 33. They indicate distances from the various sites at which a few whales may respond (20 dB S:N) and where roughly half of the whales probably will respond (30 dB S:N or 110 dB absolute received level).

Estimates of zones of responsiveness for gray whales relative to industrial noise in the Beaufort Sea must be based upon research performed in other geographic regions and then interpreted in the context of the Beaufort Sea given a definition of its acoustic environment and acoustic transmission loss characteristics.

TABLE 31. MAXIMUM ESTIMATED DISTANCES AT WHICH BOWHEAD WHALES ARE EXPECTED TO RESPOND TO DRILLSITE NOISE AT ORION AND SANDPIPER (SHALLOW SITES) UNDER TYPICAL CONDITIONS.*

Sources	20 dB S:N	30 dB S:N	110 dB
1. Two tugs, bollard	13-23 km	5-7 km	7-8 km
2. Drillship	8-12	3-4	5-6
3. Drilling on artificial island	1.8	0.2	0.3
4. Tug underway	9-15	2-4	3-5
5. Icebreakers underway	13-33	7-12	9-16

TABLE 32. MAXIMUM ESTIMATED DISTANCES AT WHICH BOWHEAD WHALES ARE EXPECTED TO RESPOND TO DRILLSITE NOISE AT HAMMERHEAD AND CORONA (INTERMEDIATE DEPTH SITES) UNDER TYPICAL CONDITIONS.*

Sources	20 dB S:N	30 dB S:N	110 dB
1. Two tugs, bollard ‘	23-34 km	7-12 km	9-14 km
2. Drillship	5-8	1	3-8
3. Drilling on artificial island	0.05	0.02	0.06
4. Tug underway	13-28	3-8	4-11
5. Icebreakers underway	7-25	2-8	4-20

*1) 20 dB signal-to-noise ratio (S:N) elicits response only in a minority of bowheads

2) 30 dB S:N elicits response in roughly half of the bowheads being exposed.

3) 110 dB absolute sound pressure level will cause roughly half of the exposed bowheads to respond.

TABLE 33. MAXIMUM ESTIMATED DISTANCES AT WHICH BOWHEAD WHALES ARE EXPECTED TO RESPOND TO DRILLSITE NOISE AT ERIK AND BELCHER (DEEP SITES) UNDER TYPICAL CONDITIONS.*

Sources	20 dB S:N	30 dB S:N	110 dB
1. Two tugs, bollard	6-10 km	1.6 km	2-4 km
2. Drillship	5-7	1-2	5-8
3. Drilling on artificial island	0.1-0.24	0.025	0.2
4. Tug underway	5-6.5	1.1	1.7
5. Icebreakers underway	6-21	1.6-6	5-18

*1) 20 dB signal-to-noise ratio (S:N) elicits response only in a minority of bowheads

2) 30 dB S:N elicits response in roughly half of the bowheads being exposed.

3) 110 dB absolute sound pressure level will cause roughly half of the exposed bowhead to respond.

Results of earlier research by BBN with migrating gray whales in California and feeding or summering gray whales near St. Lawrence Island in the Bering Sea have been used in that way for this study and the resulting data are summarized in Table 34. The threshold of responsiveness criteria used for gray whales differ somewhat from those used for bowheads, in part because they are based on a broader bandwidth (see Section 3.4.4).

It is important to state again that there are insufficient behavioral response data for either bowhead or gray whales to distinguish which of the two criteria (signal-to-noise ratio or absolute level) is the most appropriate measure to use in estimating zones of responsiveness. Hence, both criteria must be considered in any additional research which might be planned, at

TABLE 34. ZONES OF RESPONSIVENESS FOR GRAY WHALES TO DRILLSHIP NOISE IN THE BEAUFORT SEA (SEE TABLE 25 FOR DETAILS).

	Estimated Distance from Source			
			P_A = 0.1*	P_A = 0.5*
Drillsite	20 dB S:N	30 dB S:N	110 dB	120 dB
Belcher	7.4 km	1.9 km	9.6 km	2.4 km
Erik	4.9	1.3	5.9	1.4
Corona	4.6	1.1	4.8	1.4
Hammerhead	6.9	1.2	9.1	2.1
Sandpiper	9.3	4.9	8.1	3.3
Orion	9.2	4.5	8.6	3.3

*p_A = Probability of avoidance through change of swimming heading or some other avoidance maneuver.

least until a sufficient statistical base can be established to explore the question.

Tables 31 through 34 provide a summary of our present best estimates of zones of responsiveness of endangered whales to drillsite industrial noise, based on two seasons of field measurements and prior research on bowhead response to underwater noise. The interim report under this project for the 1985 portion of the work (Miles et al. 1986) provided estimates that were generally larger than those shown in this two year report. These differences are mostly due to the choice of a neutral sound speed profile to represent conditions for two years of summertime sound propagation. The calculated zones of responsiveness are sensitive to existing sound propagation characteristics.

It is emphasized that the calculated zones of responsiveness depend on many assumptions (Table 6) and that, in the case of bowheads, the information used to identify criteria of responsiveness is meager and variable. Even for a given industrial source operating at a specific site, radii of responsiveness will vary considerably from time to time. Variable propagation conditions affect the expected radii of responsiveness no matter which criterion of responsiveness is most appropriate. Normal variations in ambient noise conditions have a significant influence if the signal-to-noise ratio criteria are appropriate, although not if the whales respond to absolute noise levels. Furthermore, the sensitivity of whales to industrial noise apparently varies. Whales can react strongly to a given received noise level at one time and show no overt response to the same noise level at another time. Therefore, the radii of responsiveness quoted above must be recognized as first approximations that are applicable under average conditions. Appreciably larger and smaller radii are to be expected under various alternative conditions.

The radii of responsiveness estimated above refer to industrial sounds whose received levels are more or less continuous and stable, i.e. , to sounds from stationary and continuous sources, and to sounds from vessels that are neither approaching nor moving away. Existing data on responses of bowhead whales to boats show that the criteria used above for continuous noise do not apply to the rapidly increasing received levels of noise that occur when a boat is directly approaching. In the latter situation, bowheads exhibit strong avoidance reactions at lower received noise levels and lower boat noise : ambient noise ratios than have been used in the above calculations for continuous noise (Section 3.5).

Three sources of intermittent or fluctuating sound were also studied but were treated separately in estimating zones of responsiveness. The estimates were based on two alternative assumptions: (1) that they respond similarly to man by reacting to an average of the fluctuating acoustic energy over a specified period or (2) the assumption that bowhead whales will respond to the highest level of sound radiated. At present it is not known which assumption is more appropriate, and this leads to considerable uncertainty about zones of responsiveness around intermittent or fluctuating sources. This uncertainty requires close attention in future studies. One of the intermittent sources observed in this study, an icebreaker working on ice at a drillsite, was the most intense of all industrial sources at least during certain portions of its working duty cycle.

A brief analysis was performed to estimate zones of masking by industrial noise on the communication abilities of bowheads (Section 3.4.6). Generally, it appears that short distance communication has the potential of being impaired only when the whales are very close to industrial noise sources (e.g., a few hundreds of meters). Long distance communication, on the other hand, could be impaired at greater distances when high level sounds are being emitted from a drillsite.

4.2 Recommendations

There are a few final comments which are worthy of including here if only to highlight certain elements of the results of this two year research project.

1. As noted above, two acoustic criteria have been used in evaluating the potential zones of influence of industrial noise on endangered whales: signal-to-noise ratio and absolute received level. There is insufficient information at the present time to allow selection of one criterion over the other. Indeed, both may be appropriate under certain conditions. The issue probably cannot be resolved until the results from more field research are obtained.

2. It would be useful to acquire, on a more consistent basis than done to date, calibrated acoustic data in concert with ongoing studies of the distribution and behavior of marine mammals. Doing so would assist in determining the thresholds of responsiveness of marine mammals to noise from human activities. The addition of further industrial noise signatures to the existing database, for instance, would permit further rank-ordering of the acoustic importance of various drillsite activities.

3. A compilation of known information regarding subsea permafrost and overconsolidated clay in arctic continental shelf regions, with emphasis on developing a clearer understanding of their effect on underwater sound propagation, would be useful although somewhat academic. Even so, it would provide additional insight into the variability of underwater sound propagation in the OCS regions of the Arctic, in particular, and further understanding regarding why arctic OCS underwater sound propagation tends to be more efficient than in more temperate regions of similar water depths.

4. The predictions of zones of audibility and responsiveness of bowhead and gray whales given in this report contain uncertainties due to some lack of knowledge about certain factors and the resulting necessity for making some simplifying assumptions. Some of the more important uncertainties include

   - the variability of ambient noise level with time (which greatly affects the zone of audibility and, to a lesser extent, the zone of responsiveness,

- the variability of sound propagation characteristics, which are sensitive to changes in the sound velocity profile throughout the propagation path,
- the unknown auditory capabilities of baleen whales [e.g., if the hearing (detection) threshold is very different from 0 dB S:N, the radius of audibility will be different; the importance of long distance communication to the whales is unknown; directional hearing abilities are unknown].
- responses of whales to a given received noise level (or signal-to-noise ratio) vary; the range of variability and the factors influencing sensitivity are not well known.
- differences in whale responsiveness to continuous noise from a stationary source versus noise from a source which is variable, due either to motion or source characteristics, are not well quantified.

5. It has been demonstrated in this study that intermittent or fluctuating sound levels associated with offshore industrial operations are an important part of the acoustic environment of the Alaskan Beaufort Sea. It is important that quantified information be obtained in controlled studies regarding potential response of endangered whales to this type of source.
6. Although reactions of some whale species (including bowheads) to approaching vessels are well documented, little information has been reported regarding specific noise levels that cause these reactions. Bowhead whales are especially sensitive to this type of increasing noise and it deserves attention in future studies.

5. LITERATURE CITED

Au, W.W.L. 1980, Echolocation Signals of the Atlantic Bottlenose Dolphin (Tursiops truncatus) in Open Waters, p. 251-282. In: Animal Sonar Systems, R.-G. Busnel and J.F. Fish (eds.). Plenum, NY, 1135 p.

Au, W.W.L, D.A. Carder, R.H. Penner and B.L. Scronce. 1985, Demonstration of Adaptation in Beluga Whale Echolocation Signals, J. Acoust. Soc. Am., 77(2):726-730.

Barnes, P.W. and E. Reimnitz. 1974, Sedimentary Processes on Arctic Shelves Off the Northern Coast of Alaska, p. 439-476. In The Coast and Shelf of the Beaufort Sea. Proceedings of a Symposium, Arctic Institute of North America, 750 p.

Blasco, S.M. 1984, A Perspective on the Distribution of Subsea Permafrost on the Canadian Beaufort Continental Shelf, p. 83-86. In: Final Proceedings of the Permafrost Fourth International Conference, July 17-22, 1983, National Academy Press, Washington, D.C.

Braham, H.W., M.A. Fraker, and B.D. Krogman. 1980, Spring Migration of the Western Arctic Population of Bowhead Whales, Marine Fisheries Review, 42(9-10):36-46.

Braham, H.W. 1984, Distribution and Migration of Gray Whales in Alaska, p. 249-266. In: The Gray Whale Eschrichtius robustus, M.L. Jones, S.L. Swartz, and S. Leatherwood (eds.), Academic Press, Orlando, FL, 600 p.

Brewer, W.A., Jr., H.F. Diaz, A.S. Prechtel, H.W. Searby, J.L. Wise. 1977, Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska: Volume 111 Chukchi-Beaufort Sea, National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce. 409 p.

Carroll, G.M. and J.R. Smithhisler. 1980, Observations of Bowhead Whales During Spring Migration, Mar. Fish. Rev. 42(9-10):80-85.

Chapman, C.J. 1973, Field Studies of Hearing in Fish, Helgöl. wiss. Meeresunters. , 24:371-390.

Clark, C.W. 1983, Acoustic Communication and Behavior of the Southern Right Whale (Eubalaena Australia), p. 163-198. In: Communication and Behavior of Whales, R. Payne (cd.). AAAS Selected Symposium 76, Westview Press, Boulder, CO, 643 p.

Clark, C.W., W.T. Ellison, and K. Beeman. 1986, An Acoustic Study of the Bowhead Whales, Balaena mysticetus, off Point Barrow, Alaska, During the 1984 Spring Migration, Rep. from Marine Acoustics, Clinton, MA, for the North Slope Borough, Barrow, AK, 145 p.

Clark, C.W. and J.H. Johnson. 1984, The Sounds of the Bowhead Whale, Balaena mysticetus, During the Spring Migrations of 1979 and 1980, Can. J. Zool., 62(7):1436-1441.

Cummings, W.C. and D.V. Holliday. 1987, Sounds and Source Levels from Bowhead Whales off Point Barrow, Alaska, J. Acoust. Soc. Am. 82(3):814-821.

Cummings, W.C. and D.V. Holliday. 1985, Passive Acoustic Location of Bowhead Whales in a Population Census Off Point Barrow, Alaska, J. Acoust. Sot. Am., 78(4):1163-1169.

Cummings, W.C., D.V. Holliday and B.J. Graham. 1981a, Underwater Sound Measurements from the Prudhoe Region, Alaska, September-October 1980. Dec. No. T-81-SD-013-U, Tracer Appl . Sci., San Diego, CA, 104 p.

Cummings, W.C., D.V. Holliday and B.J. Graham. 1981b, Measurements and Localization of Underwater Sounds From the Prudhoe Region, Alaska, March, 1981. Dec. No. T-82-SD-001, Tracer Appl. Sci., San Diego, CA, 50 p.

Davis, R.A., C.R. Greene and P.L. McLaren. 1985, Studies of the Potential for Drilling Activities on Seal Island to Influence Fall Migration of Bowhead Whales Through Alaskan Nearshore Waters. Rep. from LGL Ltd., King City, Ont., for Shell Western E&P Inc., Anchorage, AK, 70 p.

Fidell, S., K.S. Pearsons, M. Grignetti, and D.M. Green. 1970. The Noisiness of Impulsive Sounds. J. Acoust. Soc. Am., 48(6), Part 1, 1304-1310.

Fields, J.M., and C.A. Powell. 1987. Community Reactions to Helicopter Noise: Results from an Experimental Study. J. Acoust . Soc. Am. 82 (2):479-492.

Fissel, D.B., J.R. Marko, J.R. Birch, G.A. Borstad and D.N. Truax. 1986, Water Mass Distributions, p. 10-63. In: W.J. Richardson (cd.), Importance of the eastern Alaskan Beaufort Sea to Feeding Bowhead Whales, 1985. OCS Study MMS 86-0026 NTIS PB87-124350. Rep. from LGL Ecol. Res. Assoc., Inc. , Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA, 315 p.

Fissel, D.B., J.R. Marko, J.R. Birch, G.A. Borstad, D.N. Truax, and R. Kerr. 1987, Water Mass Distributions, p. 11-133. In: W.J. Richardson (cd.), Importance of the Eastern Alaskan Beaufort Sea to Feeding Bowhead Whales, 1985-86, OCS Study MMS 87-0037. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA, 547 p.

Fleischer, G. 1976, Hearing in Extinct Cetaceans as Determined by Cochlear Structure, J. Paleontol. , 50(1):133-152.

Ford, J. 1977, White Whale -- Offshore Exploration Acoustic Study. Rep. from F.F. Slaney & Co., Vancouver, for Imperial Oil Ltd., Calgary. 21 p. plus Figures and Tables.

Gales, R.S. 1982a, Effects of Noise of Offshore Oil and Gas Operations on Marine Mammals -- An Introductory Assessment. NOSC Tech. Rep. 844, Vol. 1. Naval Ocean Systems Center, San Diego, CA, prepared for Bureau of Land Management, Atlantic OCS Office, N.Y., 79 p.

Gales, R.S. 1982b, Estimated Underwater Detection Ranges by Marine Mammals of Noise from Oil and Gas Platforms, p. G-1 to G-52. In: Effects of Noise of Offshore Oil and Gas Operations on Marine Mammals -- An Introductory Assessment, R.S. Gales et al. NOSC Tech. Rep. 844, Vol. 2. Naval Ocean Systems Center, San Diego, CA, prepared for Bureau of Land Management, Atlantic OCS Office, N.Y., 300 p.

Greene, C.R. 1983, Characteristics of Underwater Noise During Construction of Seal Island, Alaska, 1982, p. 118-150. In: Biological Studies and Monitoring at Seal Island, Beaufort Sea, Alaska 1982, B.J. Gallaway (cd.). Rep. from LGL Ecol. Res. Assoc., Bryan, TX, for Shell Oil Co., Houston, TX, 150 p.

Greene, C.R. 1985, Characteristics of Waterborne Industrial Noise 1980-84, p. 197-253. In: Behavior, Disturbance Responses and Distribution of Bowhead Whales Balaena mysticetus in the Eastern Beaufort Sea, 1980-84, W.J. Richardson (cd.). Ocs Study MMS 85-0034, NTIS PB87-124376. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA, 306 p.

Greene, C.R., Jr. 1987, Characteristics of Oil Industry Dredge and Drilling Sounds in the Beaufort Sea, J. Acoust. Sot. Am. 82(4):1315-1324.

Hawkins, J.E., Jr., and S.S. Stevens. 1950, The Masking of Pure Tones and of Speech by White Noise, J. Acoust. Sot. Am., 22(1):6-13.

Hickie, J. and R.A. Davis. 1983, Distribution and Movements of Bowhead Whales and Other Marine Mammals in the Prudhoe Bay Region, Alaska, 26 September to 13 October 1982, p. 84-117. In: Biological Studies and Monitoring at Seal Island, Beaufort Sea, Alaska 1982, B.J. Gallaway (cd.). Rep. from LGL Ecol. Res. Assoc., Bryan, TX, for Shell Oil Co., Houston, TX, 150 p.

Hunter, J.A.M. 1984, Geophysical Techniques for Subsea Permafrost Investigations, p. 88-89. Final Proceedings of the Permafrost Fourth International Conference, July 17-22, 1983, National Academy Press, Washington, D.C.

Hunter, J.A. and G.D. Hobson. 1975, Seismic Refraction Method of Detecting Subsea Bottom Permafrost, p. 401-416. In: Reed, J.C. and J.E. Sater (Eds.), The Coast and Shelf of the Beaufort Sea, Arctic Inst. of No. America, Arlington, VA, 750 p.

International Standards Organization. 1971. ISO/R 1996 (1971). Assessment of Noise with Respect to Community Response.

Johnson, C.S. 1968, Masked Tonal Thresholds in the Bottlenosed Porpoise, J. Acoust. Soc. Am., 44(4):965-967.

Johnson, S.R. 1984, Birds and Marine Mammals, p. 265-324. In: Environmental Characterization and Biological Use of Lagoons in the Eastern Beaufort Sea, OCSEAP Final Rep. 24, U.S. Nat. Oceanic and Atmos. Admin., Anchorage, AK.

Johnson, S.R., C.R. Greene, R.A. Davis, and W.J. Richardson. 1986, Bowhead Whales and Underwater Noise Near the Sandpiper Island Drillsite, Alaskan Beaufort Sea, Autumn 1985. Report by LGL Ltd., King City, Ontario, and Greeneridge Sciences, for Shell Western Exploration and Production, Anchorage, AK, 130 p.

Knudsen, V.O., R.S. Alford, J.W. Emling. 1944, Survey of Underwater Sound: Ambient Noise, Report No. 3, National Defense Research Committee, Div. 6, Section 6.1, Washington, DC, 246 p.

Kryter, K.D. 1985, The Effects of Noise on Man, 2nd ed. Academic Press, Orlando, FL, 688 p.

LaBelle, J.C., J.L. Wise, R.P. Voelker, R.H. Schulze, G.M. Wohl. 1983, Alaska Marine Ice Atlas, Arctic Environmental Information Data Center, University of Alaska, Anchorage, AK, 302 p.

Leggat, L.J., H.M. Merklinger, and J.L. Kennedy. 1981, LNG Carrier Underwater Noise Study for Baffin Bay, p. 115-155. In: The Question of Sound From Icebreaker Operations: The Proceedings of a Workshop, N.M. Peterson (cd.). Arctic Pilot Proj., Petro-Canada, Calgary, Alberta, 350 p.

LGL Ltd. 1986. Reactions of Beluga Whales and Narwhals to Ship Traffic and Ice-Breaking Along Ice Edges in the Eastern Canadian High Arctic: 1982-1984. Environ. Stud. No. 37, Indian and Northern Affairs Canada, Ottawa, 301 p.

Ljungblad, D.K., P.O. Thompson, and S.E. Moore. 1982, Underwater Sounds Recorded from Migrating Bowhead Whales, Balaena mysticetus, in 1979, J. Acoust. Soc. Am., 71(2):477-482.

Ljungblad, D.K., S.E. Moore, J.T. Clarke, D.R. Van Schoik, and J.C. Bennett. 1985a, Aerial Surveys of Endangered Whales in the Northern Bering, Eastern Chukchi, and Alaskan Beaufort Seas, 1984: With a Six Year Review, 1979-1984. OCS Study MMS 85-0018. NOSC Tech. Rep. 1046, Naval Ocean Systems Center, San Diego, CA, for U.S. Minerals Management Service, Anchorage, AK, 302 p.

Ljungblad, D.K., B. Würsig, S.L. Swartz, and J.M. Keene. 1985b, Observations on the Behavior of Bowhead Whales (Balaena mysticetus) in the Presence of Operating Seismic Exploration Vessels in the Alaskan Beaufort Sea. OCS Study MMS 85-0076. Rep. from SEACO, Inc., San Diego, CA, for U.S. Minerals Manage. Serv., Anchorage, AK, 88 p.

Ljungblad, D.K., S.E. Moore, J.T. Clarke. 1986a, Assessment of Bowhead Whale (Balaena mysticetus) Feeding Patterns in the Alaskan Beaufort and Northeastern Chukchi Seas via Aerial Surveys, Fall 1979-84, Rep. Int. Whal. Comm., 36:265-272.

Ljungblad, D.K., S.E. Moore, J.T. Clarke, and J.C. Bennett. 1986b, Aerial Surveys of Endangered Whales in the Northern Bering, Eastern Chukchi, and Alaskan Beaufort Seas, 1985: With a Seven Year Review, 1979-85, NOSC Tech. Rep. 1111, OCS Study MMS 86-0002, Naval Ocean Systems Center, San Diego, CA, 409 p.

Ljungblad, D.K., S.E. Moore, J.T. Clarke, J.C. Bennett. 1987, 'Distribution, Abundance, Behavior and Bioacoustics of Endangered Whales in the Alaskan Beaufort and Eastern Chukchi Seas, 1979-86, NOSC Tech. Rep. 1177, OCS Study MMS 87-0039, Naval Ocean Systems Center, San Diego, CA, for U.S. Minerals Manage. Serv., 391 p.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyack, and J.E. Bird. 1983, Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior. BBN Report No. 5366, Bolt Beranek and Newman Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK, variously paginated.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyack, and J.E. Bird. 1984, Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior. Phase II: January 1984 Migration. BBN Report No. 5586, Bolt Beranek and Newman Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK, variously paginated.

Malme, C.I., P.R. Miles, P. Tyack, C.W. Clark, and J.E. Bird. 1985, Investigation of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Feeding Humpback Whale Behavior, Report No. 5851, BBN Laboratories Incorporated, for Minerals Management Service, Anchorage, AK, variously paginated.

Malme, C.I. and R. Mlawski. 1979, Measurements of Underwater Acoustic Noise in the Prudhoe Bay Area. BBN Technical Memorandum No. 513, Bolt Beranek and Newman Inc., Cambridge, MA, for Exxon Production Research Co., 74 p.

Malme, C.I., B. Würsig, J.E. Bird, and P. Tyack. 1986a, Behavioral Responses of Gray Whales to Industrial Noise: Feeding Observations and Predictive Modeling, BBN Report No. 6265 prepared by BBN Laboratories Incorporated, Cambridge, MA, for NOAA, Anchorage, AK, variously paginated.

Malme, C.I., P.W. Smith, Jr., and P.R. Miles. 1986b, Study of the Effects of Offshore Geophysical Acoustic Survey Operations on Important Commercial Fisheries in California, Report No. 6125, BBN Laboratories Inc., for Battelle-Santa Barbara, variously paginated.

Marquette, W.M. and H.W. Braham. 1982, Gray Whale Distribution and Catch by Alaskan Eskimos: A Replacement for the Bowhead Whale? Arctic, 35 (3):386-394.

Marsh, H.W. and M. Schulkin. 1962, Shallow Water Sound Transmission, J. Acoust. Sot. Am., 34(6), pp. 863-864.

McLaren, P.L., C.R. Greene, W.J. Richardson, and R.A. Davis. 1986, Bowhead Whales and Underwater Noise Near A Drillship Operation in the Alaskan Beaufort Sea, 1985, Report by LGL Ltd., King City, Ontario, and Greeneridge Sciences Inc. for UNOCAL, Anchorage, AK, 137 p.

Miles, P.R., C.I. Malme, G.W. Shepard, W.J. Richardson and J.E. Bird. 1986, prediction of Drilling Site-Specific Interaction of Industrial Acoustic Stimuli and Endangered Whales: Beaufort Sea (1985), BBN Report No. 6185, OCS Study MMS 86-0046, NTIS PB87-124343, BBN Laboratories Incorporated for Minerals Management Service, Anchorage, AK, 312 p.

Moore, P.W.B. and R.J. Schusterman. 1987, Audiometric Assessment of Northern Fur Seals, Callorhinus ursinus, Mar. Mamm. Sci. 3(1):31-53.

Moore, S.E., J.T. Clarke, and D.K. Ljungblad (1986), A Comparison of Gray Whale (Eschrictius robustus) and Bowhead Whale (Balaena mysticetus) Distribution, Abundance, Habitat Preference and Behavior in the Northeastern Chukchi Sea, 1982-84. Rep. Int. Whal. Comm. 36:273-279.

Moore, S.E., D.K. Ljungblad and D.R. Schmidt. No date [1984], Ambient, Industrial and Biological Sounds Recorded in the Northern Bering, Eastern Chukchi and Alaskan Beaufort Seas During the Seasonal Migrations of the Bowhead Whale (Balaena mysticetus), 1979-1982. Report from SEACO, Inc., San Diego, CA, for U.S. Minerals Manage. Serv., Anchorage, AK, 104 p.

Morack, J.L. and J.C. Rogers. 1984, Acoustic Velocities of Nearshore Materials in the Alaskan Beaufort and Chukchi Seas, p. 259-274. In: P.W. Barnes et al. (eds.), The Alaskan Beaufort Sea Ecosystems and Environments, Academic Press, Orlando, FL, 466 p.

Morack, J.L., H.A. MacAuley, and J.A. Hunter. 1983, Geophysical Measurements of Subbottom Permafrost in the Canadian Beaufort Sea, p. 866-876. Permafrost Fourth International Conference, July 17-22 1983, National Academy Press, Washington, DC, 1524 p.

Naidu, A.S., T.C. Mowatt, S.E. Rawlinson, and H.V. Weiss. 1984, Sediment Characteristics of the Lagoons of the Alaskan Beaufort Sea Coast, and Evolution of Simpson Lagoon, p. 275-292. In: P.W. Barnes et al. (eds.) The Alaskan Beaufort Sea Ecosystems and Environments, Academic Press, Orlando, FL, 466 p.

Neave, K.G. and P.V. Sellmann. 1984, Determining Distribution Patterns of Ice-Bonded Permafrost in the U.S. Beaufort Sea from Seismic Data, p. 237-258. In: P.W. Barnes et al. (eds.), The Alaskan Beaufort Sea Ecosystems and Environments, Academic Press, Orlando, FL, 466 p.

Norris, J.C. and S. Leatherwood. 1981, Hearing in the Bowhead Whale, Balaena mysticetus, as Estimated by Cochlear Morphology p. 745-787. In: Tissue Structural Studies and Other Investigations on the Biology of Endangered Whales in the Beaufort Sea, Volume II, report from University of Maryland, Dept. of Veterinary Science, for U.S. Bureau of Land Management, Anchorage, AK, 953 p.

Payne, R. and D. Webb. 1971, Orientation by Means of Long Range Acoustic Signaling in Baleen Whales, Ann. N.Y. Acad. Sci., 188:110-141.

Pearsons, K.S. 1966, The Effects of Duration and Background Noise Level on Perceived Noisiness, Report FAA-ADS-78, Bolt Beranek and Newman Inc., Cambridge, MA, for the U.S. Federal Aviation Agency, Washington, D.C., variously paginated.

Peterson, N.M. (cd.). 1981, The Question of Sound From Icebreaker Operations: The Proceedings of a Workshop. Arctic Pilot Proj., Petro-Canada, Calgary, Alberta, 350 p.

Popper, A.N. 1980, Sound Emission and Detection by Delphinids, p. 1-52. In: Cetacean Behavior: Mechanisms and Functions, L.M. Herman (cd.), J. Wiley, New York, 463 p.

Richardson, W.J., C.R. Greene, J.P. Hickie, and R.A. Davis. 1983, Effects of Offshore Petroleum Operations on Cold Water Marine Mammals. A Literature Review. API Report No. 4370. Am. Petrol. Inst., Washington, DC, 248 p.

Richardson, W.J. (cd.) 1983. Behavior, Disturbance Responses and distribution of Bowhead Whales Balaena mysticetus in the Eastern Beaufort Sea, 1982. NTIS PB86-205879. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA. **357 p.**

Richardson, W.J. (cd.), 1985, Behavior, Disturbance Responses and Distribution of Bowhead Whales Balaena mysticetus in the Eastern Beaufort Sea, 1980-84, OCS Study MMS 85-0034, NTIS PB87-124376. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA. 306 p.

Richardson, W.J., C.R. Greene, and B. Würsig. 1985a, Behavior, Disturbance Responses and Distribution of Bowhead Whales Balaena mysticetus in the Eastern Beaufort Sea, 1980-84: A Summary, OCS Study MMS 85-0034, NTIS PB87-124368, Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA, 30 p.

Richardson, W.J., M.A. Fraker, B. Würsig, and R.S. Wells. 1985b, Behaviour of Bowhead Whales Balaena mysticetus Summering in the Beaufort Sea: Reactions to Industrial Activities. Biol. Conserv., 32(3):195-230.

Richardson, W.J., B. Würsig, and G.W. Miller. 1987, "Bowhead Distribution, Numbers, and Activities." p. 257-368. In: Importance of the Eastern Alaskan Beaufort Sea to Feeding Bowhead Whales, 1985-86," W.J. Richardson (cd.), OCS Study MMS 87-0037. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA. 547 p.

Richardson, W.J., R.S. Wells, and B. Würsig 1985c, Disturbance Responses of Bowheads, 1980-84, p. 89-196. In: Behavior, Disturbance Responses and Distribution of Bowhead Whales Balaena mysticetus in the Eastern Beaufort Sea, 1980-84, W.J. Richardson (cd.), OCS Study MMS 85-0034, NTIS PB87-124376. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA, 306 p.

Richardson, W.J., B. Würsig, G.W. Miller, and G. Silber. 1986, Bowhead Distribution, Numbers and Activities. p. 146-219 In: Importance of the Eastern Alaskan Beaufort Sea to Feeding Bowhead Whales, 1985, W.J. Richardson (cd.), OCS Study MMS 86-0026, NTIS PB87-124350. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA, 315 p.

Richardson, W.J. and C.I. Malme. 1986, Previous Data on Responses of Bowhead and Gray Whales to Noise from Drilling and Island Construction, p. 204-290 (App. B). In: Miles et al. 1986, q.v.

Robinson, D.W., J.M. Bowsher, and W.C. Copeland. 1963, On Judging the Noise from Aircraft in Flight, Acoustics 13(5):324-336.

Rugh, D.J. and M.A. Fraker. 1981, Gray Whale (Eschrichtius robustus) Sightings in Eastern Beaufort Sea. Arctic 34(2):186-187.

Smith, P.W., Jr. 1971, The Averaged Impulse Response of a Shallow-Water Channel, J. Acoust. Sot. Am.,50(1), pp. 332-336.

Smith, P.W., Jr. 1986, Low Frequency Rolloff in the Response of Shallow-Water Channels, J. Acoust. Sot. Am., 79, pp. 71-75.

Spofford, C.W., R.R. Green, and J.B. Hersey. 1983, The Estimation of Gee-Acoustic Ocean Sediment Parameters from Measured Bottom-Loss Data, Report SAI-83-879-WA, Science Applications Inc., McLean, VA, for Nav. Ocean Res. Dev. Activ., NSTL Station, MS, variously paginated.

Spieth, W. 1956, Annoyance Threshold Judgments of Bands of Noise, J. Acoust. Sot. Am., 28:872-877.

Terhune, J.M. 1981, Influence of Loud Vessel Noises on Marine Mammal Hearing and Vocal Communication, p. 270-286. In: N.M. Peterson (cd.), The Question of Sound From Icebreaker Operations: The Proceedings of a Workshop. Arctic Pilot Proj., Petro-Canada, Calgary. 350 p.

Terhune, J.M. and K. Ronald. 1971, The Harp Seal, Pagophilus groenlandicus (Erxleben, 1777). X. The Air Audiogram. Can. J. Zool., 49:385-390.

Terhune, J.M. and K. Ronald. 1975, Masked Hearing Thresholds of Ringed Seals, J. Acoust. Soc. Am., 58(2):515-516.

Thompson, T.J., H.E. Winn, and P.J. Perkins. 1979, Mysticete sounds, p. 403-431. In: Behavior of Marine Animals, Vol. 3, Cetaceans, H.E. Winn and B.L. Olla (eds.), Plenum Press, New York, 438 p.

Thomson, D.H. and W.J. Richardson. 1987. Integration. p. 449-479. In: W.J. Richardson (cd.), Importance of the Eastern Alaskan Beaufort Sea to Feeding Bowhead Whales, 1985-1986. OCS Study MMS 87-0037. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA. 547 p.

Tyack, P. and H. Whitehead. 1983, Male Competition in Large Groups of Wintering Humpback Whales, Behaviour, 83(1-2):132-154.

Urick, R.J. 1983, Principles of Underwater Sound for Engineers, McGraw Hill, New York, 3rd Edition, 423 p.

Verrall, R. 1981, Acoustic Transmission Losses and Ambient Noise in Parry Channel, p. 220-233. In: The Question of Sound from Icebreaker Operations: The Proceedings of a Workshop, N.M. Peterson (cd.), Arctic Pilot Proj., Petro-Canada, Calgary, 350 p.

Watkins, W.A. 1981, Activities and Underwater Sounds of Fin Whales, Sci. Rep. Whales Res. Inst., 33:83-117.

Weinberg, H. 1985, Generic Sonar Model, NUSC Technical Dec. #5971D, Naval Underwater Systems Center, New London, CT, variously paginated.

Wenz, G.M. 1962, Acoustic Ambient Noise in the Ocean: Spectra and Sources, J. Acoust. Soc. Am., 34(12):1936-1956.

Weston, D.E. 1976, Propagation in Water With Uniform Sound Velocity but Variable-Depth Lossy Bottom, J. Sound. Vib., 47:473-483.

Würsig, B., E.M. Dorsey, W.J. Richardson, C.W. Clark, and R. Payne. 1985, Normal Behavior of Bowheads, 1980-84, p. 13-88. In: W.J. Richardson (cd.), Behavior, Disturbance Response and Distribution of Bowhead Whales Balaena mysticetus in the Eastern Beaufort Sea, 1980-84. OCS Study MMS 85-0034, NTIS PB87-124376. Report from LGL Ecol. Res. Assoc. Inc., Bryan, TX, for U.S. Minerals Management Service, Reston, VA, 306 p.

Zaytseva, K.A., A.I. Akopian, and V.P. Morozov. 1975, Noise Resistance of the Dolphin Auditory Analyzer as a Function of Noise Direction, Biofizika, 20(3):519-521. (Transl. JPRS-65762, NTIS 297212, 4 p.).

APPENDIX A

BOWHEAD WHALE MIGRATION IN RELATION TO SELECTED DRILLSITES

APPENDIX A: BOWHEAD WHALE MIGRATION IN RELATION TO SELECTED DRILLSITES

It is useful to summarize briefly the migration habits of the bowhead in relation to the study area and the selected operational sites. Figure A.1 includes a general indication of the routes and/or corridors for spring and fall migration. The spring migration route in the April-early June period heads eastward from near Point Barrow to 90-170 km offshore following open leads in 8/10-10/10 ice cover conditions. Most of the spring migration route through the Alaskan Beaufort Sea is in deep water north of the continental shelf edge. Ljungblad (1985a) and Braham et al. (1980) provide ample evidence of the regularity of the spring migration route. Swimming speeds are generally between 3 and 8 km/h (Carroll and Smithhisler 1980) and behavior consists primarily of traveling with some social activity once the whales leave the Barrow area. Ljungblad distinguishes between the specific migration corridor and the broad migration route since his year-to-year observations generally show that the "corridor" width may change from year-to-year and that the general route is relatively invariant. The general impression from the results of Ljungblad, Braham and others is that the offshore spring route is probably dictated by ice conditions. Bottom fast ice and floating fast ice extend north from the coastline beyond the offshore shoal regions on the North Slope. In early spring the 10/10 solid ice cover extends far offshore.

The fall west-bound migration pattern is equally repeatable in all reported observations, with the Ljungblad data-base being the largest (Ljungblad et al. 1985a, 1986a,b, 1987). A few bowheads start to leave their traditional summering grounds in the Canadian Beaufort Sea in August, but many whales do not enter Alaskan waters until late September or early October. In their

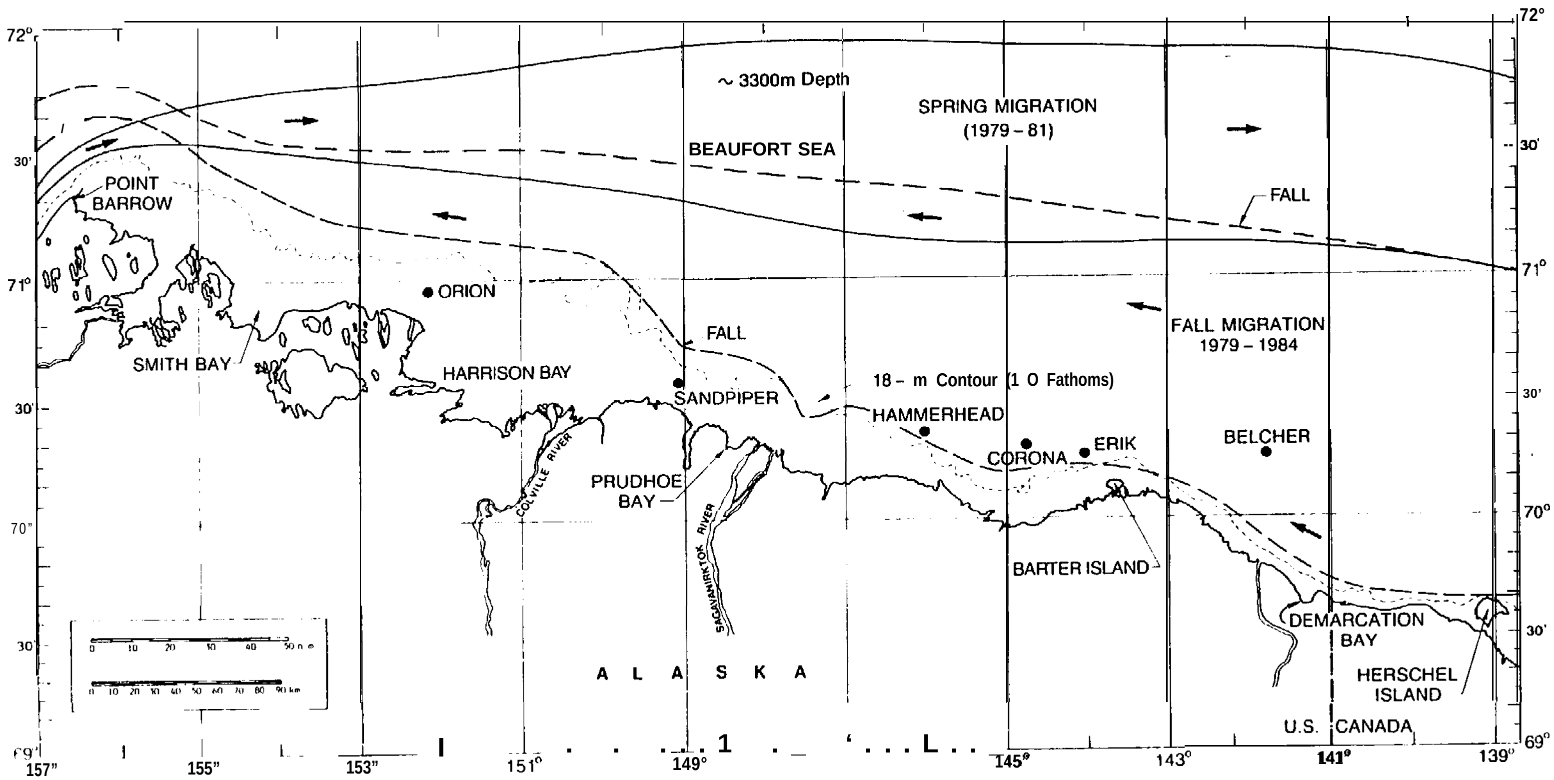


FIG. Al. APPROXIMATE BOWHEAD WHALE MIGRATION COORIDORS AND SELECTED DRILLSITES (SUMMARY BASED ON LJUNGBLAD 1985a, 1986a, 1986a,b; BRAHAM 1980).

westerly movement, the bowheads travel roughly parallel to the coastline, with most being offshore of the 18-meter (10 fathom) bathymetric contour. The 18-meter contour also defines the general location of shoal regions in-shore of that contour. However, some bowheads are observed in water shallower than 18 m and are usually feeding; this was especially evident in 1982 and 1986 (Johnson 1984; Richardson et al. 1987). The inshore fall migration route may be related to the need to continue summer feeding wherever possible during the return to the Chukchi and northern Bering Sea regions for the winter. Ljungblad et al. (1985a, 1986a) and Richardson et al. (1987) report that feeding bowheads tend to migrate within a corridor which is approximately 40-50 km wide with the southern boundary at or just inshore of the 18-meter contour. However, some westbound bowheads occur far offshore; this was particularly evident during 1983, when Ljungblad et al. reported non-feeding fall migrants as much as .120 km offshore, traveling in the southern region of the spring corridor. Their southern boundary was again at about the 18-m contour. The westward migration is often slow (~1 km/hr). It is interrupted by feeding, and whale calls are frequently heard. In heavy ice years, the fall swimming rate is fast (3 to 5.5 km/hr) and there seem to be few calls.

Drill-site noise is probably undetectable to bowheads in the spring migration corridor which is 90-170 km offshore of the nearshore drillsites. However, the potential exposure to detectable site noise during the fall migration is high. Note that Hammerhead, Corona, Erik and Belcher are all located within the migration corridor. Sandpiper and Orion are 18-28 km south of the southern edge of the fall migration corridor as described by Ljungblad et al. (1985a). Prior to this study, bowheads had occasionally been seen during fall migration in the general areas where oil exploration was underway as well as near the deeper industrial sites of this study (Hickie and Davis 1983; Davis et al. 1985; Ljungblad et al. 1985a, 1985c). Data on whale distribution in 1985-86 near the sites investigated in this study were obtained during several investigations, including Ljungblad et al. (1986b, 1987), Johnson et al. (1986), McLaren et al. (1986), Richardson et al. (1986,1987), and LGL Ltd. (in preparation).

APPENDIX B

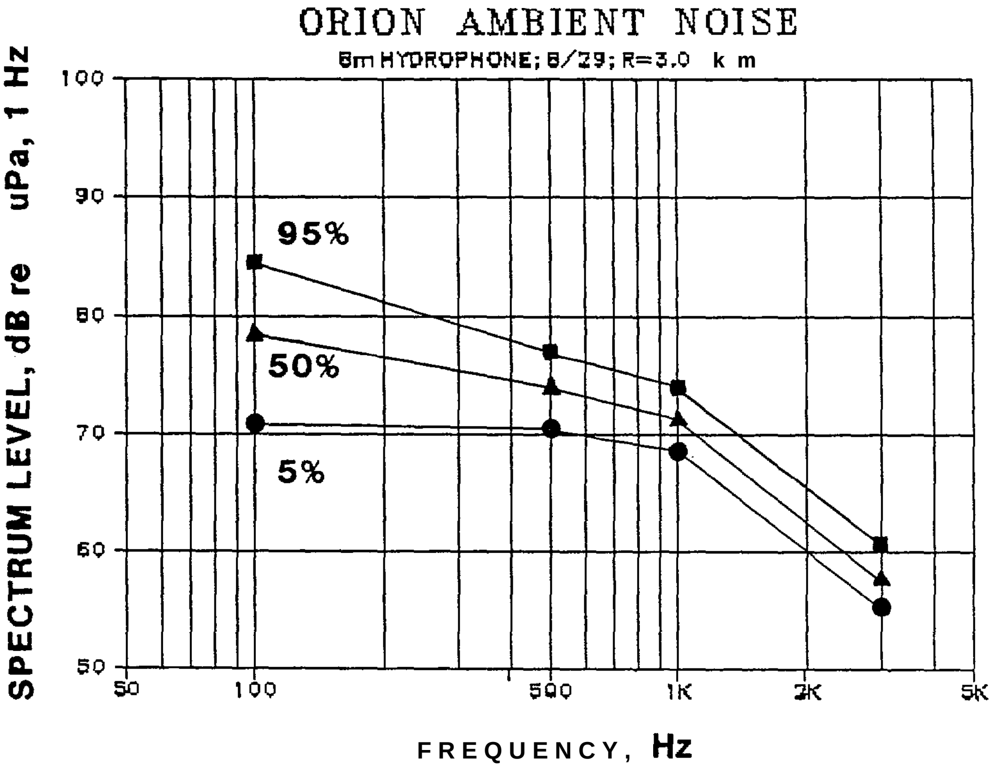
SHORT-TERM AMBIENT NOISE STATISTICS FOR THE ALASKAN BEAUFORT SEA IN 1985

APPENDIX B: SHORT-TERM AMBIENT NOISE STATISTICS FOR THE ALASKAN BEAUFORT SEA IN 1985

The following figures, extracted from the interim report under this project (Miles et al. 1986), are a statistical description of the ambient noise measured in the Alaskan Beaufort Sea under this project in the August-September 1985 period. The recorded data were analyzed so as to derive the 95th, 50th, and 5th percentile cumulative distribution functions for the noise level at 100, 500, 1000, and 3000 Hz existing during the measurement period indicated in each figure. That is, the upper curve in each figure represents the ambient noise level which is equal to or less than the level given 95% of the time. The 50% curve is the median ambient noise level existing at the time of measurement and the 5th percentile curve indicates the level of noise which exists or is less than that noted 5% of the time. As indicated, the noise levels are presented for an analysis bandwidth of 1 Hz (spectrum level). The measurement conditions relating to wind, sea state, ice, water depth, and hydrophore depth are also noted in each figure.

Data from the shallow sites Orion and Sandpiper (Figs. B.1 through B.5) and the deep site, Corona (Figs. B.6 through B.7) have been used to estimate 1/3 octave band ambient levels according to 10 log (bandwidth), where bandwidth equals one-third octave band or 23% of the center frequency. Knowledge of historical wind and ice statistics in the region (Brewer et al. 1977; LaBelle et al. 1983) and their relationship to ambient noise (Urick, 1983; Wenz 1962; Moore, et al. n.d. [1984]), all listed in Section 6, Literature Cited, has allowed additional adjustment. The resulting one-third octave band curves are contained in Section 3.1 of this report provide a description of the ambient noise statistics for the Alaskan Beaufort Sea during the mid-August to mid-September time period. The data from

Corona have been used in the description of the noise statistics at the other three deep sites as well (Hammerhead, Erik, and Belcher).

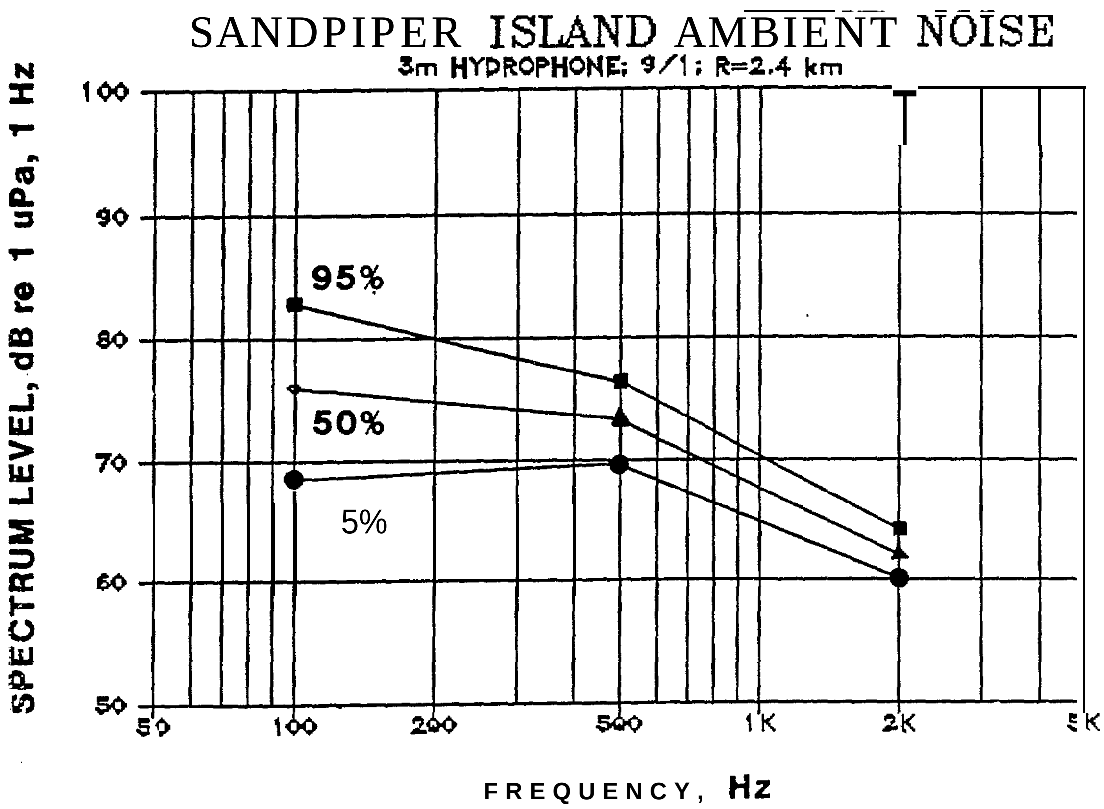


Measurement Conditions:

Wind: "light"
Sea State: O–1
Ice: 1/10-2/10

Water Depth: 16 m
Hydro Depth: 8 m

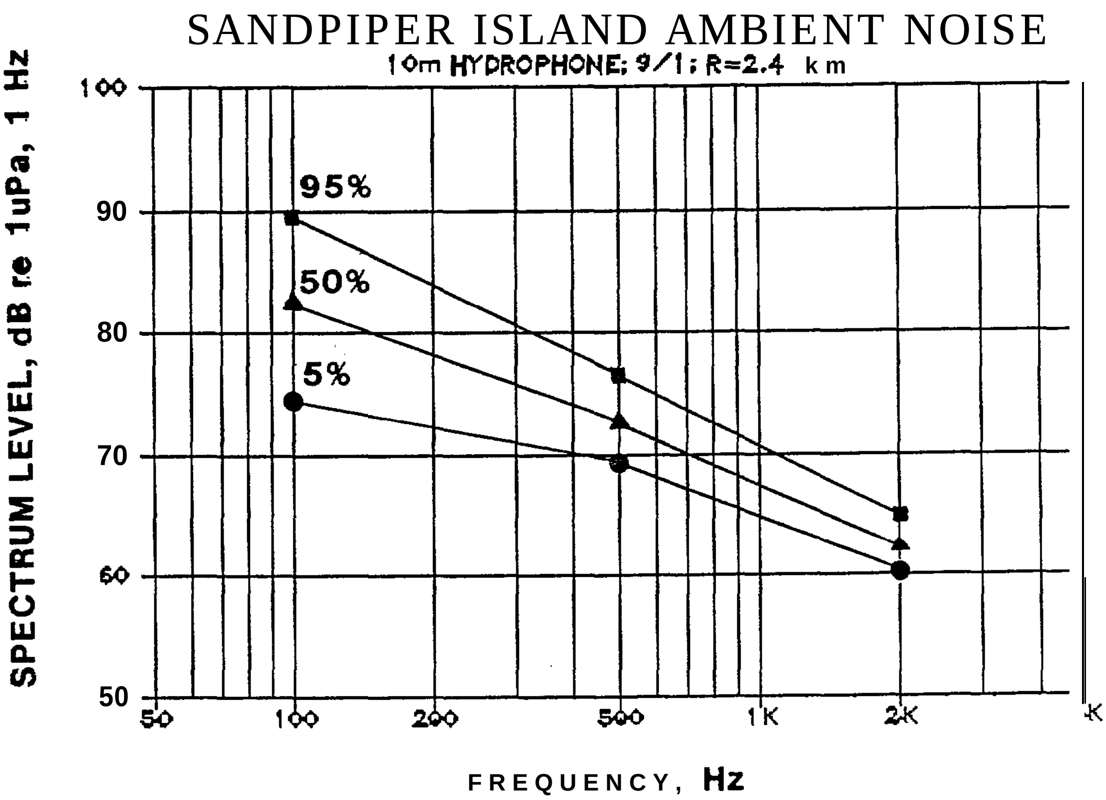
FIGURE B.1. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES AT THE ORION SITE, 8/29/85. HYDROPHORE AT 8 m DEPTH. VALUES ARE IN TERMS OF' SPECTRUM LEVEL (1 HZ BANDWIDTH).



Measurement Conditions:

Wind:	10-15 kt	Water Depth:	11 m
Sea State:	1-2	Hydro Depth:	3 m
Ice:	6/10-8/10		

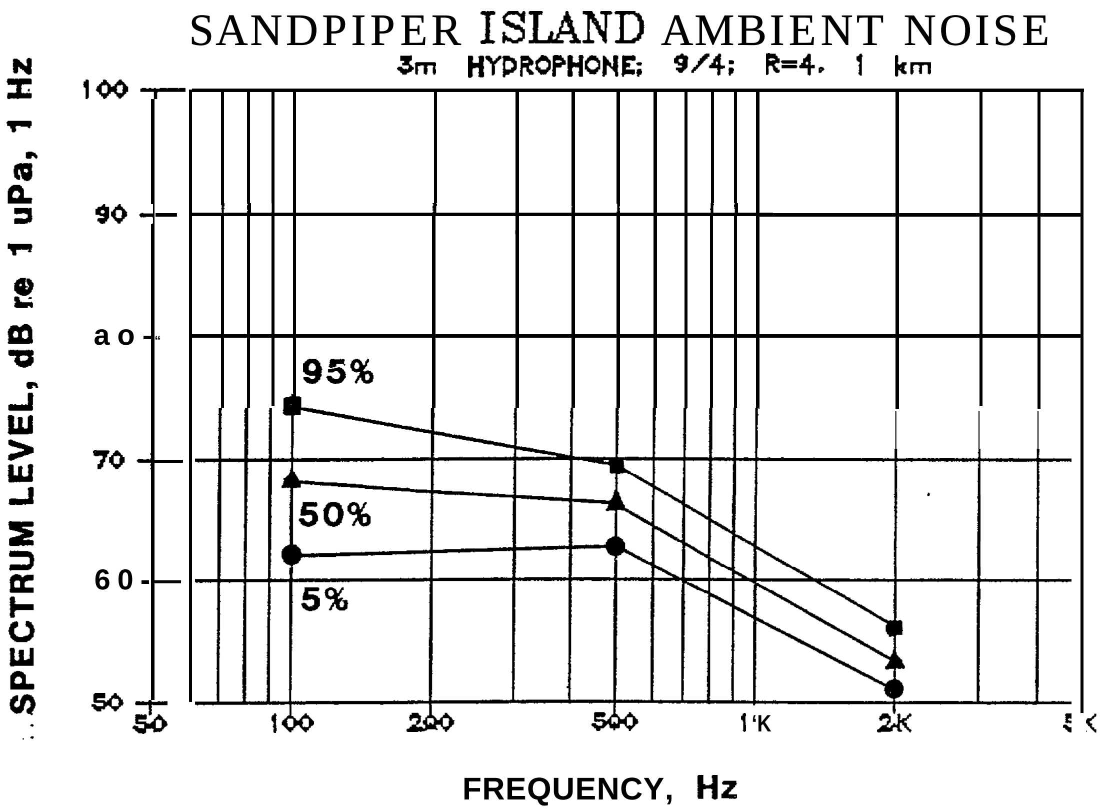
FIGURE B.2. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES NEAR SANDPIPER ISLAND, 9/1/85. HYDROPHORE AT 3 m DEPTH . VALUES ARE IN TERMS OF SPECTRUM LEVEL (1 HZ BANDWIDTH).



Measurement Conditions:

Wind:	**10–15 kt**	**Water Depth:**	**11 m**
Sea State:	**1–2**	**Hydro Depth:**	**10 m**
Ice:	**6/10–8/10**		

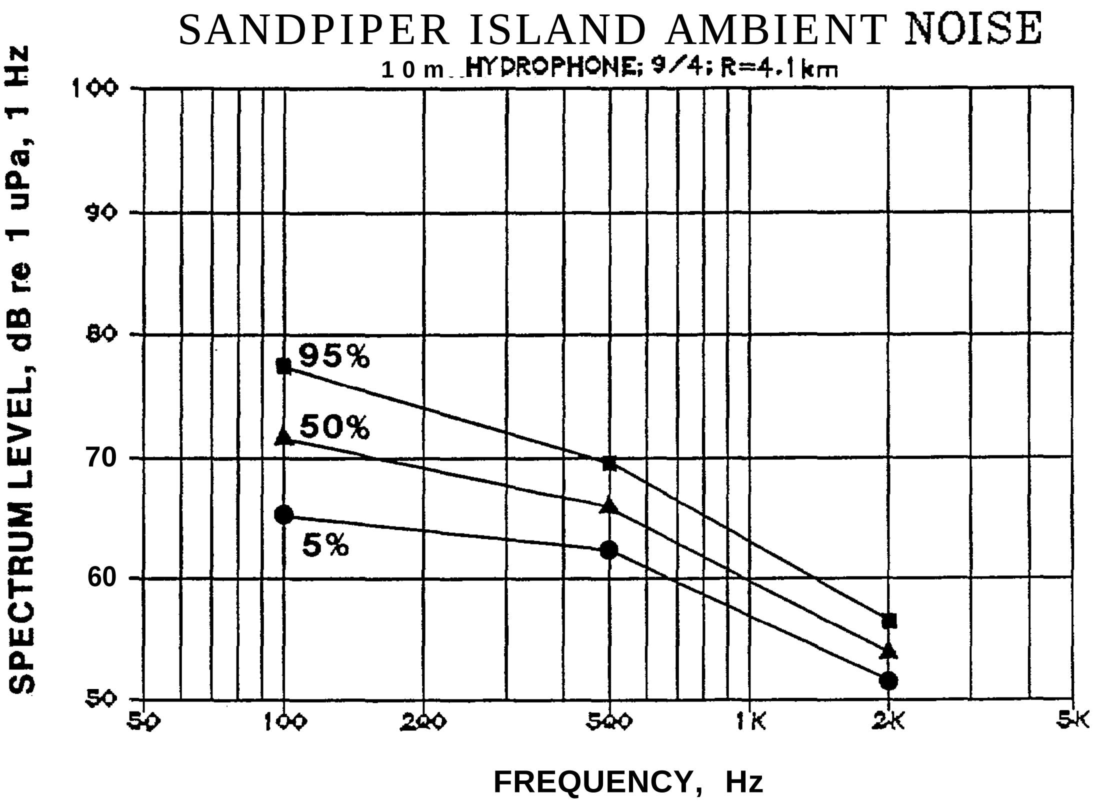
FIGURE B.3. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES NEAR SANDPIPER ISLAND, 9/1/85. HYDROPHORE AT 10 m DEPTH . VALUES ARE IN TERMS OF SPECTRUM LEVEL (1 HZ BANDWIDTH) .



Measurement Conditions:

Wind:	"light"	Water Depth:	14 m
Sea State:	0-1	Hydro Depth:	3 m
Ice:	1/10-2/10		

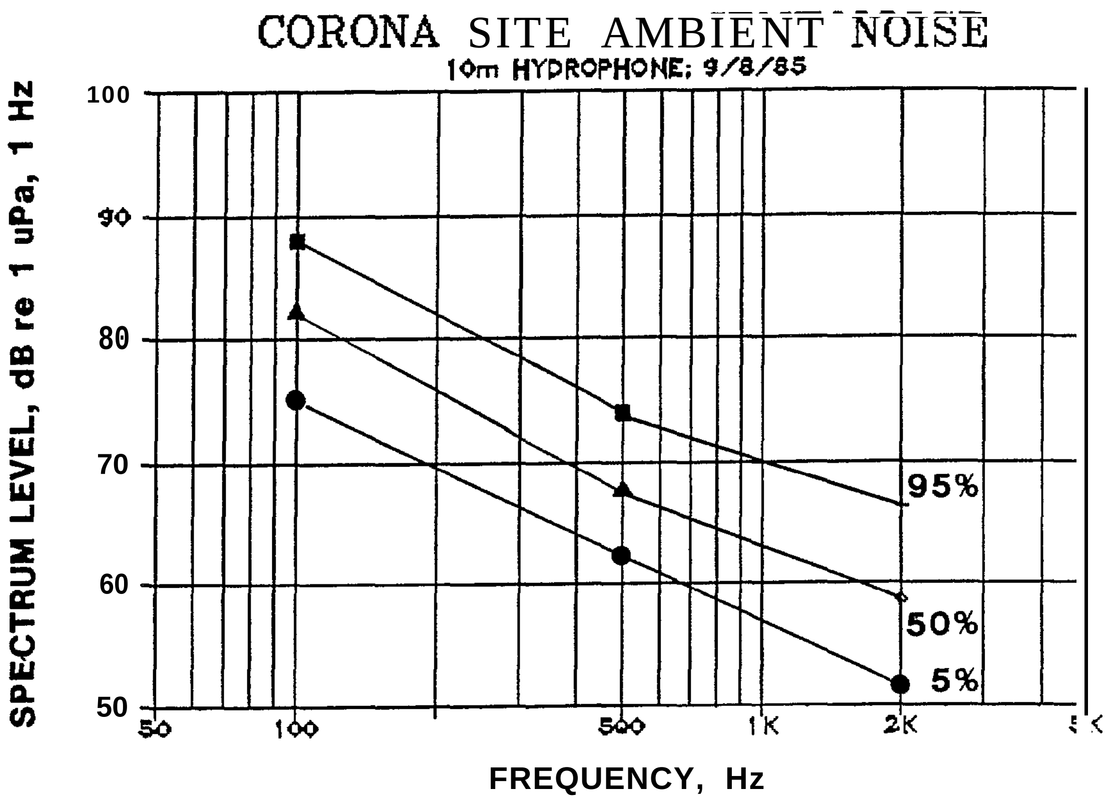
FIGURE B.4. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES NEAR SANDPIPER ISLAND, 9/4/85. HYDROPHORE AT 3 m DEPTH . VALUES ARE IN TERMS OF SPECTRUM LEVEL (1 HZ BANDWIDTH) .



Measurement Conditions:

Wind:	"light"	Water Depth:	14 m
Sea State:	0-1	Hydro Depth:	10 m
Ice:	1/10-2/10		

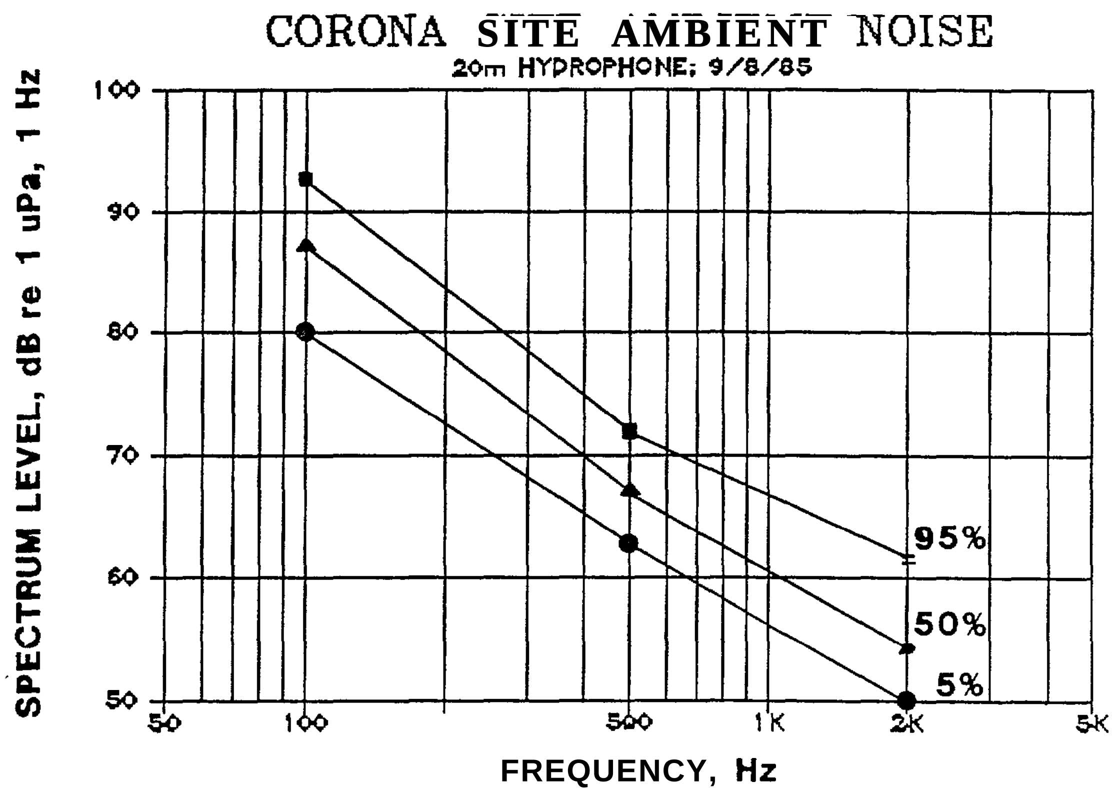
FIGURE B.5. **MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES NEAR SANDPIPER ISLAND, 9/4/85. HYDROPHORE AT 10 m DEPTH. VALUES ARE IN TERMS OF SPECTRUM LEVEL (l HZ BANDWIDTH).**



Measurement Conditions:

Wind:	10-15 kt	Water Depth:	35 m
Sea State:	3	Hydro Depth:	10 m
Ice:	O		

FIGURE B.6. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES AT THE CORONA SITE, 9/8/85. HYDROPHORE AT 10 m DEPTH . VALUES ARE IN TERMS OF SPECTRUM LEVEL (1 HZ BANDWIDTH) .



Measurement Conditions:

Wind:	10-15 kt	Water Depth:	35 m
Sea State:	3	Hydro Depth:	20 m
Ice:	O		

FIGURE B.7. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES AT THE CORONA SITE, 9/8/85. HYDROPHORE AT 20 m DEPTH . VALUES ARE IN TERMS OF SPECTRUM LEVEL (1 HZ BANDWIDTH) .

APPENDIX C:

TRANSMISSION LOSS MODEL PROGRAM LISTING AND TABULATION OF TRANSMISSION LOSS CHARACTERISTICS

APPENDIX C: TRANSMISSION LOSS MODEL PROGRAM LISTING AND TABULATION OF TRANSMISSION LOSS CHARACTERISTICS

C.1 Transmission Loss Model

The procedure developed by Weston (1976) for prediction of transmission loss in shallow water under isospeed or low gradient conditions was adapted by P.W. Smith, Jr., for use on a Hewlett Packard Model 9845 computer. This program is written as a subroutine which is accessed by a graphics plot program to show transmission loss characteristics for a specified set of input parameters. Documentation for the required input is contained in comment lines within the program. This subroutine is written in HP BASIC and can be adapted for other computers by changing the HP specific command lines. A main program routine is required to provide range increment steps in kilometers and receive the program output.

WESTON/SMITH MODEL LISTING

```
5220 Func:  SUB Func(T,I)
5230  OPTION BASE 0
5240  DEG
5250  COM X(*),Y(*)
5260  ! Program "WESTON"; 20 Jan 1986; P.W.Smith,Jr., BBN Labs.
5270  ! Transmission loss in isospeed water with lossy, sloping bottom of
5280  ! constant slope. Based largely on D.E.Weston, JSV 47,473-483(1976)
5290  ! with some additions from BBN Rept 2320(1972).
5300 Param:F=4000 ! frequency (Hz)
5310  Rmark(0)=Rmark(1)=Rmark(2)=Rmark(3)=0
5320  Hs=55 ! water depth at source  (m)
5330  Cs=1435  ! sound speed  (m/s)
5340  L=0   ! Slope of the bottom
5350  An=5  !  Local Anomaly, dB
5360  Phicrit=.80
5370  ! sine of critical angle of bottom; for slow bottoms, use value 1.
5380  ! (I know that seems irrational !)
5390  B=1   ! Bottom loss parameter defined in comment below
5400 Pat-end:  ! 4.343*b*sine(d/e) = dBloss/ bounce
5410  R=1000*T  ! T is range in km
5415  Fs=(.001*F)^2
5420  Av=(.1*Fs/(1+Fs)+40*Fs/(4100+Fs)+.000275*Fs+.003)*1.0936
5425  ! Volumetric absorption  (dB/km) (Thorp JASA 42:270, 1967)
5430  Lambda=Cs/F   ! wavelength (m)
5440  C=PI/(2*B*Phicrit^2)
5450  Hr=Hs+L*R
5460  Hav=(Hs+Hr)/2
5470  Ra=Hr/(2*Phicrit)
5480  Rb=C*Hs^2/Hav
5490  Phi1=Lambda/(2*Hr)
5500  IF (Hr>0)AND(Phi1<1) THEN 5550
5510    ! Results are meaningless if program reaches here.
5520    X(I)=T
5530    Y(I)=999
5540    SUBEXIT
5550  Phieff=SQR(2*Hs^2/(B*R*Hav))
5560  IF B*R*Hav*Hr<90000*Hs^2/4 THEN Rmark(3)=T
5570  ! This formula come from Eq (34) of BBN Rept 2320, using a radius of
5580  ! curvature value of 90000 m, appropriate to pressure effect in isothermal
5590  ! water. It represents the maximum range at which it is reasonable to
5600  ! ignore the speed gradient.  Use your own value to get a better test.
5610  !
5620  !
5630  X(I)=T
5640  IF Phi1>Phieff THEN D
5650  ON 1+(R>Ra)+(R>Rb) GOTO A,B,C
5660 A: Y(I)=20*LGT(R)-An                              ! spherical spreading
5670  Rmark(0)=T
5680  SUBEXIT
5690 B: Y(I)=10*LGT(R*Ra)-An                           ! transitional cylindrical
5700  Rmark(1)=T
5710  SUBEXIT
5720 C: Y(I)=10*LGT(R*Hs/(SQR(PI)*(Phieff-.5*Phi1)))-An+Av*T    ! mode stripping
5730  Rmark(2)=T
5740  SUBEXIT
5750 D: Y(I)=10*LGT(R*Hs*Hr/Lambda)+R*Lambda^2*Hav*B/((Hs*Hr)^2*1.842)-An+Av*T
5755  ! one mode
5760  ! The number 1.842 comes from 8/4.343.
5770  !
5780  ! Output are: (i) a set of values of transmission loss,Y(I)dB//1m,and
5790  ! range, X(I) km; (ii) Rmark(0), the max range for spherical spreading;
5800  ! Rmark(1), the max range for transitional cylindrical spreading;
5810  ! Rmark(2), the max range for multimodal, mode stripping ("15log R"),
5820  ! which is followed by a single mode domain; Rmark(3),which is the
5830  ! maximum range at which one ought to believe these formulas that
5840  ! ignore all depthwise speed gradients.
5850  SUBEND
```

C.2 Tabulation of Transmission Loss Characteristics

The results of the analysis of the transmission loss measurements described in Section 3.3.2 are tabulated in the following Tables Cl through C7. These tables have been derived from the measured data using the Generic Multipath Model to correct the data to neutral SVP conditions. The tables show the Weston/Smith TL characteristic for the neutral SVP condition together with the TL differences estimated to be produced by the measured or predicted variations in SVP during the whale migration period. The downward refracting gradient condition (d_{grad}) would be expected to be present at the sites during the early part of the migration through about mid-September. This would be followed by a period of nearly neutral SVP conditions and then, near freeze-up, a surface duct ($sd_{uc}t$) condition would begin to develop.

The TL characteristic for the appropriate condition at a given site can be estimated by adding the correction factor under ‘he ‘grad ‘r ‘duct column to the TL value in the neutral column for the frequency of interest shown in the tables. A measurement of the SVP condition at the site should be made and compared to the SVP data reported in Section 3.3.3 in order to determine which column to use. For SVP conditions that fall between the profiles shown, an intermediate value of TL can be estimated using linear interpolation.

TABLE C1.

Weston/Smith Transmission- Loss Data, 1986, (Corrected for neutral SVP)
Belcher, East TL data (sheet rev. 4/7/87)

	100 Hz			200 Hz			500 Hz			1 kHz			2 kHz			4 kHz		
Range(km)	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct
0.1	n	30.4			36.6			37.0			41.6			38.4			47.6	
0.2	o	33.4			39.6			41.4			44.6	-0.3		41.4			50.6	
0.4		36.4			42.6			44.4			47.6	-0.6		44.4	-0.4	-0.2	53.6	-0.3
0.6	s	39.2			44.4			46.2	-0.3		49.4	-1.1		46.2	-0.7	-0.4	55.4	-0.5
0.8	i	41.1			45.7			47.4	-0.5		50.7	-1.7	-0.3	47.4	-1.1	-0.6	56.7	-0.7
1.0	g	42.6			46.6	-0.4		48.4	-0.7	-0.4	51.6	-2.1	-0.5	48.4	-1.7	-1.0	57.6	-1.1
2	n	47.3	-0.3	0.3	49.6	-0.8		51.4	-1.6	-0.9	54.6	-4.3	-1.2	52.3	-2.9	-2.1	60.7	-2.3
4	i	52.2	0.9	0.3	52.6	-0.9		54.4	-1.7	-0.2	58.6	-4.4	-0.8	56.8	-3.0	-1.4	65.3	-1.8
6	f	55.1	1.1	0.3	55.4	-2.0		56.2	-1.9	0.5	61.2	-4.5	-0.4	59.5	-3.1	-0.7	67.9	-1.3
8	i	57.3	1.8	0.3	57.4	-2.8		57.4	-2.1	0.6	63.1	-4.6	0.0	61.3	-3.2	-0.1	69.8	-0.8
10	c	59.0	1.9	0.3	58.9	-2.9		59.0	-2.3	0.8	64.6	-4.7	0.4	62.8	-3.3	0.5	71.3	-0.3
12	a	60.4	2.0	0.4	60.1	-2.9		60.2	-2.4	1.5	65.8	-4.8	0.7	64.0	-3.2			
14	n	61.6	2.3	0.5	61.2	-3.2		61.2	-2.5	1.9	66.8	-4.9	1.2	65.0	-3.1			
16	t	62.7	2.4	0.6	62.1	-3.6	0.3	62.1	-2.6	2.4	67.7	-5.0	1.5	65.9	-3.0			
18		63.7	2.4	0.7	63.0	-3.8	0.4	62.9	-2.7	2.8	68.5	-5.1	1.8	66.7	-2.8			
20	c	64.6	2.3	0.8	63.7	-4.1	0.5	63.6	-2.9	3.2	69.2	-5.3	2.2	67.4	-2.6			
24	h	67.0	1.0	1.1	65.0	-4.1	0.8	64.9	-2.6	4.0	70.4	-4.9	3.2	68.6	-1.9			
30	a	69.3	0.2	1.4	66.6	-4.0	1.1	66.4	-2.2	5.4	71.9	-4.4	4.4	70.0	-0.9			
34	n	70.6	0.2	1.6	67.5	-3.7	1.4	67.2	-1.6	6.1	72.7	-4.0	5.5	70.9	-0.2			
40	g	72.6	0.1	1.9	68.7	-3.3	1.7	68.3	-0.9	7.5	73.8	-3.4	6.7	71.9	0.6			
44	e	73.9	0.0	2.3	69.4	-3.1	2.1	69.0	-0.9	8.6	74.4	-3.2						
50		75.7	-0.5	2.8	70.4	-2.8	2.5	69.9	-0.8	9.2	75.3	-2.9						

TABLE C.2.

Weston/Smith Transmission-Loss Data, 1986, (Corrected for neutral SVP)
Belcher North TL, combining E and N TL data (sheet rev. 4/24/87)
Combined TL Estimate

	100 Hz			200 Hz			500 Hz			1 kHz			2 kHz			4 kHz		
Range(km)	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct
0.1	n	30.4			36.6			37.0			41.6			38.4			47.6	
0.2	0	33.4			39.7			41.4	41.4		44.7	-0.3		41.4			50.7	
0.4		36.4			42.7			44.5			47.7	-0.6		44.4	-0.4	-0.2	53.7	-0.3
0.6	s	39.2			44.5			46.2	-0.3		49.5	-1.1		46.2	-0.7	-0.4	55.5	-0.5
0.8	i	41.1			45.7			47.5	-0.5		50.7	-1.7	-0.3	47.5	-1.1	-0.6	56.7	-0.7
1.0	g	42.6			46.7	-0.4		48.5	-0.7	-0.4	51.7	-2.1	-0.5	48.5	-1.7	-1.0	57.7	-1.1
2	n	47..4	-0.3	0.3	49.9	-0.8		51.6	-1.6	-0.9	54.9	-4.3	-1.2	52.3	-2.9	-2.1	60.8	-2.3
4	i	52.2	0.9	0.3	53.1	-0.9		54.9	-1.7	-0.2	58.7	-4.4	-0.8	56.9	-3.0	-1.4	65.4	-1.8
6	f	55.1	1.1	0.3	55.5	-2.0		56.8	-1.9	0.5	61.4	-4.5	-0.4	59.6	-3.1	-0.7	68.1	-7.3
8	i	57.2	1.8	0.3	57.5	-2.8		57.7	-2.1	0.6	63.3	-4.6	0.0	61.6	-3.2	-0.1	70.0	-0.8
10	c	59.3	1.9	0.3	59.2	-2.9		59.4	-2.3	0.8	65.0	-4.7	0.4	63.2	-3.3	0.5	71.5	-0.3
12	a	61.4	2.0	0.4	61.0	-2.9		61.2	-2.4	1.5	66.8	-4.8	0.7	63.9	-3.2			
14	n	64.2	2.3	0.5	63.1	-3.2		63.1	-2.5	1.9	68.8	-4.9	1.2	66.2	-3.1			
16	t	66.4	2.4	0.6	64.8	-3.6	0.3	64.7	-2.6	2.4	70.5	-5.0	1.5	67.5	-3.0			
18		68.7	2.4	0.7	66.5	-3.8	0.4	66.4	-2.7	2.8	72.1	-5.1	1.8	68.8	-2.8			
20	c	71.5	2.3	0.8	68.5	-4.1	0.5	68.3	-2.9	3.2	74.1	-5.3	2.2	70.2	-2.6			
24	h	75.1	1.0	1.1	71.2	-4.1	0.8	70.9	-2.6	4.0	76.8	-4.9	3.2	72.2	-1.9			
30	a	79.2	0.2	1.4	74.4	-4.0	1.1	74.0	-2.2	5.4	79.9	-4.4	4.4	74.7	-0.9			
34	n	80.2	0.2	1.6	75.4	-3.7	1.4	74.9	-1.6	6.1	80.9	-4.0	5.5	75.6	-0.2			
40	g	81.4	0.1	1.9	76.6	-3.3	1.7	76.2	-0.9	7.5	82.1	-3.4	6.7	76.9	0.6			
44	e	82.2	0.0	2.3	77.4	-3.1	2.1	76.9	-0.9	8.6	82.9	-3.2		77.6				
50		83.2	-0.5	2.8	78.4	-2.8	2.5	77.9	-0.8	9.2	83.9	-2.9		78.6				

TABLE C.3.

Weston/Smith Transmission-Loss Data, 1986, (Corrected for neutral SVP)
Erik, North TL data (sheet rev. 4/28/87)

	100 Hz			200 Hz			500 Hz			1 kHz			2 kHz			4 kHz		
Range(km)	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct
0.1		36.0			39.3		1.9	39.3	0.5	0.2	41.3	0.4	0.3	39.3	0.4	0.3	43.3	0.5
0.2		39.0			42.3		1.1	42.3	-0.3	0.4	44.3	-0.9	0.5	42.3	-0.3	0.6	46.3	0.2
0.4		42.0			45.3		1.2	45.3	-1.2	0.8	47.3	-1.9	1.0	45.3	-1.8	1.2	49.3	-0.9
0.6		43.8			47.1	-0.3	1.7	47.1	-1.8	1.2	49.1	-2.6	1.4	47.1	-2.4	1.8	51.1	-1.6
0.8		46.0	0.3		48.4	-0.6	2.3	48.4	-2.5	1.6	50.4	-3.2	1.8	48.4	-3.2	2.3	52.4	-2.1
1.0		47.5	0.5	0.3	49.4	-0.9	2.8	49.4	-3.2	2.0	51.4	-3.8	2.2	49.4	-4.0	2.8	53.4	-3.0
2	0.3	52.3	0.8	0.5	52.5	-1.2	3.6	52.9	-4.1	2.8	55.4	-.4.4	2.8	53.4	-4.4	3.6	57.5	-3.4
4	0.7	57.2	1.6	0.7	56.3	-1.9	5.2	57.5	-5.8	4.4	60.1	-5.4	3.9	58.0	-4.8	3.8	62.1	-2.7
6	0.8	60.1	1.9	1.0	59.1	-2.6	7.7	60.3	-7.6	6.9	62.8	-5.3	5.9	60.7	-4.8	5.1	64.8	-2.1
8	1.1	62.3	2.2	1.3	61.1	-2.9	10.4	62.3	-6.9	11.7	64.8	-5.8	9.5	62.6	-5.2	10.1	66.8	-1.2
10	1.3	63.9	2.5	1.4	62.7	-3.5	13.2	63.8	-7.6	12.2	66.3	-7.1	11.4	64.1	-5.4	11.4	68.3	-0.6
12	1.6	65.3	2.9	1.5	64.0	-3.7	16.0	65.1	-7.6	15.0	67.5	-7.3	14.2	65.4	-4.9	14.8	69.5	0.3
14	2.0	66.5	3.1	1.6	65.1	-4.0	18.3	66.2	-7.9	17.6	68.6	-7.5	17.7	66.5	-4.5	17.7	70.6	1.4
16	2.2	67.5	3.2	1.7	66.1	-4.2	20.8	67.1	-8.1	19.4	69.5	-7.7	20.2	67.4	-4.4	20.8	71.5	2.2
18	2.4	68.4	3.3	1.8	67.0	-4.3	22.9	67.9	-0.3	21.8	70.4	-7.7	22.8	68.2	-4.3	23.9	72.3	3.1
20	2.5	69.2	3.3	2.0	67.7	-4.4	24.7	68.7	-8.5	24.3	71.1	-7.6	25.8	68.9	-3.5	26.0	73.0	3.7
24	2.6	70.7	3.4	2.2	69.1	-4.7	27.7	70.0	-8.7	28.1	72.4	-7.2	30.1	70.2	-2.8			
30	2.8	72.4	3.6	2.4	70.7	-5.2	29.7	71.6	-9.1	30.9	74.0	-7.1	34.3	71.8	-1.6			
34	2.9	73.4	3.7	2.5	71.7	-5.6	31.5	72.5	-9.0	32.9	74.9	-7.0	36.7	72.7	-0.9			
40	3.1	74.7	3.6	2.6	72.9	-4.3	32.9	73.7	-8.5	34.4	76.1	-6.3	38.3	73.9	0.2			

TABLE C.4.

Weston/Smith Transmission-Loss Data, 1986, (Corrected for neutral SVP)
Corona North TL data (sheet rev. 4/7/87)

	100 Hz			200 Hz			500 Hz			1 kHz			2 kHz			4 kHz		
Range(km)	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct
0.1	0.8	37.4	0.5	1.2	36.7	0.3	2.1	28.4	0.7	0.2	28.7	0.4	0.2	18.6	0.4	0.6	24.9	0.7
0.2	0.6	40.5	0.5	0.5	39.7	0.0	1.3	33.0	-0.2	1.1	33.2	-0.5	-0.4	23.2	-0.3	-1.5	29.4	0.0
0.4	0.6	43.5	0.5	0.1	42.7	-0.2	1.0	37.6	-1.6	1.4	37.8	-2.1	1.4	27.7	-2.0	0.7	33.9	-1.8
0.6	0.6	45.3	0.5	0.8	44.5	-0.2	0.7	40.3	-2.1	0.8	.40.4	-2.3	1.4	30.4	-2.8	1.3	36.6	-2.2
0.8	0.6	46.5	0.7	0.9	45.8	-0.4	1.1	42.2	-2.6	0.8	42.3	-3.8	1.4	32.3	-3.7	1.4	38.4	-2.6
1.0	0.6	47.5	0.9	0.9	46.8	-0.6	1.5	43.7	-2.9	1.2	43.8	-4.0	1.4	33.7	-4.0	1.2	39.9	-3.4
2		50.7	0.8	1.3	51.4	-0.9	1.7	48.4	-4.1	1.7	48.4	-5.3	1.4	38.3	-5.3	1.0	44.5	-3.3
4		53.9	0.7	1.3	56.4	-1.4	2.3	53.2	-5.9	2.7	53.1	-6.0	2.2	42.9	-5.4	0.7	49.1	-2.6
6		58.8	0.7	1.3	59.3	-1.9	3.2	56.0	-6.6	4.2	55.9	-6.2	4.5	45.7	-5.6	2.4	51.8	-1.9
8		62.0	0.6	1.3	61.5	-2.4	4.8	58.0	-6.9	5.9	57.8	-7.5	4.8	47.6	-5.9	2.7	53.7	-0.3
10		64.0	0.6	1.3	63.2	-3.0	5.6	59.6	-7.5	6.7	59.4	-7.8	5.9	49.1	-5.9	3.9	55.2	0.0
12		65.7	0.6	1.4	64.5	-3.2	6.6	60.9	-7.8	8.2	60.6	-7.9	7.5	50.4	-5.5	4.4	56.5	0.7
14		67.2	0.7	1.4	65.7	-3.4	7.7	62.0	-8.1	9.7	61.7	-8.0	9.1	51.5	-4.8	4.9	57.6	1.7
16		68.5	0.7	1.4	66.8	-3.6	8.5	63.0	-8.6	11.0	62.7	-8.0	10.7	52.4	-4.5	6.0	58.5	2.5
18		69.7	0.8	1.4	67.7	-3.8	9.3	63.8	-9.0	12.3	63.5	-8.0	12.3	53.2	-4.3	7.2	59.3	3.4
20		70.7	0.9	1.4	68.5	-3.9	10.1	64.6	-9.5	13.6	64.3	-8.1	13.9	54.0	-4.1	8.3	60.0	4.2
24		72.6	1.1	1.3	69.9	-4.3	12.1	65.9	-9.3	16.7	65.6	-7.7						
30		74.9	1.4	1.2	71.7	-4.8	14.6	67.6	-9.0	20.4	67.2	-7.6						

TABLE C.5.

Weston/Smith Transmission-Loss Data, 1986, (Corrected for neutral SVP)
Hammerhead, North TL data (sheet rev 4/7/87)

	100 Hz			200 Hz			500 Hz			1 kHz			2 kHz			4 kHz		
Range(km)	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct
0.1	n	33.0		n	38,0	n	n	34.0		0.3	30.0	0.4	0.3	16.9	0.2	0.3	19.8	0.4
0.2	0	36.0		0	41,0	o	0	37.0		0.5	33.0	-0.3	0.4	21.5	-0.4	0.4	24.3	-0.3
0.4		39.0			44.0			40.0		0.6	36.0	-1.5	0.8	26.0	-1.5	0.8	28.9	-1.8
0.6	s	40.8		s	45.8	s	s	41.8		0.9	37.8	-1.9	1.2	28.7	-2.1	1.1	31.5	-2.6
0.8	i	42.1		i	47.1	i	i	43.1		1.1	39.1	-2.8	2.0	30.6	-3.3	1.9	33.4	-3.7
1.0	9	43.1		9	48.1	9	9	44.1		1.5	40.1	-3.1	2.6	32.0	-3.3	2.4	34.9	-3.4
2	n	46.1	0.2	n	51.1	n	n	47.1	-0.2	2.8	43.1	-4.6	2.8	36.6	-5.0	2.7	39.4	-5.0
4		49.3	0.2		54.3			50.5	-0.3	5.0	47.2	-5.6	6.4	41.2	-6.3	6.2	44.0	-6.3
6		52.8	0.4		56.2			53.3	-0.5	7.9	49.9	-6.1	8.7	43.9	-7.5	8.8	46.7	-6.9
8	c	55.0	0.5	c	58.5	c	c	55.3	-0.6	10.1	51.8	-6.3	12.5	45.9	-7.4	11.9	48.6	-7.2
10	h	56.7	0.5	h	60.1	h	h	56.8	-0.7	12.4	53.4	-6.5	14.5	47.4	-8.3	14.0	50.1	-7.5
12	a	58.2	0.4	a	61.4	a	a	58.0	-0.8	14.5	54.6	-6.6	17.3	48.6	-8.1			
14	n	59.4	0.5	n	62.5	n	n	59.1	-0.9	16.8	55.7	-6.8	19.0	49.7	-8.5			
16	9	61.4	0.5	9	63.4	g	9	60.0	-1.0	19.0	56.6	-7.0	20.6	50.6	-8.7			
18	e	62.4	0.5	e	64.3	e	e	60.9	-1.2	20.8	57.4	-7.2						
20		63.3	0.4		65.0			61.6	-1.2	22.6	58.1	-7.3						

TABLE C.6.

Weston/Smith Transmission-Loss Data, 1986, (Corrected for neutral SVP)
Sandpiper North TL data (sheet rev. 4/7/87)

	100 Hz			200 Hz			500 Hz			1 kHz			2 kHz			4 kHz		
Range(km)	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct
0.1		24.7			24.7			25.7			25.7			20.5			26.4	
0.2		27.8			27.8			29.7			31.3			25.0			31.0	
0.4		30.8			32.6			34.3			35.9			29.6			35.5	
0.6		32.6			35.5			37.1			38.6			32.3	-0.4		38.2	-0.4
0.8		35.4			37.5			39.0			40.5		0.4	34.2	-0.9		40.1	-1.0
1.0	0.4	37.0		0.4	39.2		0.4	40.6		0.4	42.0		0.6	35.7	-1.6		41.5	-1.8
2	0.8	42.3		0.8	44.3		0.6	45.4		0.8	46.7		1.4	40.3	-2.2	0.4	46.2	-2.4
4	1.3	48.9	-0.5	0.9	49.8		0.6	50.4		1.0	51.5		3.6	45.0	-3.1	1.7	50.8	-4.2
6	1.4	52.8	-0.4	1.1	54.1	-0.4	0.9	53.3		1.3	54.4		5.2	47.8	-4.3	3.7	53.6	-5.0
8	1.4	55.7	-0.7	1.3	56.7	-0.4	1.2	55.5		1.4	56.6		7.0	49.9	-5.0	5.5	55.6	-5.4
10	1.7	58.1	-0.4	1.5	58.7	-0.4	1.3	57.1	-0.4	1.5	58.1		7.8	51.4	-5.5	7.2	57.2	-5.9
12	2.2	60.0		1.7	60.5	-0.4	1.5	58.5	-0.4	1.5	59.4		10.6	52.7	-5.8	9.1	58.4	-6.3
14	2.4	61.7		1.9	62.0	-0.4	1.8	59.7	-0.4	1.6	60.5		12.3	53.8	-6.1	11.1	59.5	-6.9
16	2.6	63.1		2.0	63.2	-0.9	2.0	60.7	-0.4	1.6	61.5	0.2	14.1	54.8	-6.4	13.1	60.5	-6.8
18	2.7	64.4		2.3	64.4	-0.6	2.0	61.6	-0.4	1.6	62.4	0.4	15.7	55.7	-6.6			
20	2.8	65.5		2.5	65.4	-0.3	2.4	62.4	-0.4	1.7	63.2	0.4	17.3	56.5	-6.8			

TABLE C.7.

Weston/Smith Transmi ssi on- Loss Data, 1986, (corrected for neutral SVP)
Orion, North TL (1985 TL data, 1986 Sandpiper data) (sheet rev. 4/7/87)

	100 Hz			200 Hz			500 Hz			1 kHz			2 kHz			4 kHz		
Range(km)	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct	dgrad	TL(dB)	sduct
0.1		24.5			21.5			25.5			30.4			26.3			30.2	
0.2		27.5			24.5			29.1			35.0			30.8			34.8	
0.4		30.6			29.6			33.7			39.6			35.4			39.3	
0.6		32.4			32.5			36.4			42.3			38.1	-0.4		42.0	-0.4
0.8		35.4			34.5			38.4			44.3		0.4	40.1	-0.9		43.9	-1.0
1.0	0.4	37.1		0.4	36.2		0.4	39.9	-0.3	0.4	.45.8		0.6	41.6	-1.6		45.4	-1.8
2	0.8	42.5		0.8	41.4		0.6	44.8	-0.3	0.8	50.6		1.4	46.3	-2.2	0.4	50.0	-2.4
4	1.3	49.3	-0.5	0.9	47.8		0.6	49.7	-0.3	1.0	55.4		3.6	51.1	-3.1	1.7	54.8	-4.2
6	1.4	53.2	-0.5	1.1	51.3	-0.4	0.9	52.7	-0.3	1.3	58.4		5.2	54.0	-4.3	3.7	57.6	-5.0
8	1.4	56.1	-0.5	1.3	53.9	-0.4	1.2	54.8	-0.3	1.4	60.4		7.0	56.1	-5.0	5.5	59.6	-5.4
10	1.7	58.5	-0.5	1.5	56.0	-0.5	1.3	56.5	-0.4	1.5	62,1		7.8	57.7	-5.5	7.2	61.2	-5.9
12	2.2	60.4		1.7	57.7	-0.5	1.5	57.8	-0.4	1.5	63.4		10.6	59.0	-5.8	9.1	62.5	-6.3
14	2.4	61.9		1.9	59.1	-0.5	1.8	59.0	-0.4	1.6	64.6		12.3	60.2	-6.1	11.1	63.7	-6.9
16	2.6	63.3		2.0	60.4	-0.5	2.0	60.0	-0.4	1.6	65.6	0.2	14.1	61.2	-6.4	13.1	64.6	-6.8
18	2.7	64.5		2.3	61.5	-0.5	2.0	60.9	-0.4	1.6	66.5	0.4	15.7	62.0	-6.6			
20	2.8	65.5		2.5	62.4	-0.5	2.4	61.7	-0.4	1.7	67.3	0.4	17.3	62.8	-6.8			

APPENDIX D

SOUND PROPAGATION ESTIMATES FOR ZONE OF INFLUENCE ANALYSES

APPENDIX D: SOUND PROPAGATION ESTIMATES FOR ZONE OF INFLUENCE ANALYSES*

This appendix summarizes the sound propagation analyses used to derive the estimated ranges of detectability and responsiveness (see section 3.4). The six tables in this appendix are for the six industrial sites discussed in detail in Section 3.4: Orion, Sandpiper; Hammerhead, Corona, Erik and Belcher. For each of these sites, we have hypothesized that each of nine industrial activities might occur:

- dredge bucket being raised (as recorded at Erik),
- tug ARCTIC FOX towing a barge (as recorded at Erik),
- two tugs in operation in bollard condition (as recorded at Sandpiper),
- icebreaker CANMAR KIGORIAK underway at 10 kt in open water,
- icebreaking supply ship ROBERT LEMEUR underway at 10 kt in open water,
- ROBERT LEMEUR pushing ice,
- drillship EXPLORER II drilling (as recorded at Corona),
- drilling on artificial island (as recorded at Sandpiper by Greenridge Sciences Inc.), and
- tug ARCTIC FOX underway (as recorded at Erik).

It should be recognized that an artificial island like that at Sandpiper would not be built at sites as deep as Hammerhead, Corona, Erik, or Belcher. Similarly, a drillship is unlikely to operate at sites as shallow as Orion or Sandpiper. Hence, some of the calculations in this appendix are of only theoretical relevance.

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For each of the nine industrial activities, Section 3.4.1 identifies the l/3-octave bands in which the source levels are especially high relative to ambient levels in the same bands. One to five such l/3-octave bands were identified for each of the nine industrial sources. These bands are the ones that are likely to be detectable at longest ranges, and that will have the highest "industrial to ambient" noise ratios at any given distance. These bands are the ones considered in this appendix.

The Weston shallow-water sound propagation models (section 3.3) have been applied for each of the six sites, nine industrial sources, and 1-5 frequency bands. For Orion and Sandpiper, we considered east and west azimuths (bottom slope O) and north azimuths (bottom slope positive). For Hammerhead, Corona, Erik, and Belcher, we also considered south azimuths (bottom slope negative) . (For Belcher, east/west and south propagation are considered, but northward propagation is excluded; no one Weston/Smith sound propagation model was suitable for northward propagation from Belcher.)

The tabulated data for each run of the propagation model include:

- frequency and source level (1/3-octave band) of the industrial noise in the l/3-octave band with high "industrial to ambient" noise ratio,
- the ambient noise levels expected in the corresponding l/3-octave band at the site in question (5th, 50th and 95th percentile values),
- the ranges at which the received industrial noise level would be expected to equal the 5th, 50th and 95th percentile ambient noise (assumed "zone of audibility"),
- the ranges at which the received industrial noise level would be expected to be 10 dB, 20 dB, 30 dB and 40 dB

above the median (50th percentile) ambient noise (used to define “zone of responsiveness”),

- **the** ranges at which the absolute received industrial noise level would be expected to be 100, 110, 120 and 130 dB, and
- the maximum range at which the propagation model is believed to be reasonably reliable.

Section **3.4** includes additional rationale for this approach, and an interpretation of the results.

Estimated ranges at which various noise levels would be received if one of nine industrial activities took place at the ORION site. For each industrial source, we consider the few 1/3-octave banda in which noise levels were highest relative to the median ambient noise level.

Freq (Hz)	1/3 OB S Lev (dB)	5% Amb i (dB)	Median Amb i (dB)	95% Amb i (dB)	Dirtn from Site	RLev= 5%Amb (km)	RLev= Med Amb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli-able
ERIK. DREDGE																	
250	162	60	84	95	E/W	45	25	16	17	9.6	4.1	1.2	13	6	2.1	.523	20
					North	>50	>50	40	44	14	4.4	1.2	22	7.5	2.1	.522	20
750	158	61	84	96	E/W	>50	36	13	17	5	1.2	.284	7.8	2	.476	.108	20
					North	>50	51	14	18	4.9	1.2	.283	7.8	2	.474	.108	18
1250	158	60	82	94	E/W	>50	38	14	17	5.1	1.3	.288	6.2	1.6	.362	.08	20
					North	>50	45	14	17	5	1.2	.288	6.1	1.6	.36	.08	12
ERIK.TUG & BARGE																	
1000	170	60	82	94	E/W	>50	>50	34	39	18	5.5	1.4	21	7.1	1.8	.427	20
					North	>50	>50	43	51	19	5.4	1.4	23	7.1	1.8	.425	15
3500	164	58	78	90	E/W	>50	>50	29	33	15	4.9	1.3	12	3.1	.919	.208	16
					North	>50	>50	27	31	14	4.8	1.3	12	3.6	.91	.207	8.5
SANDP.TUGS--Bollard condition																	
300	163	61	84	95	E/W	>50	32	20	21	11	4.6	1.2	15	6.8	2.2	.55	20
					North	>50	>50	44	50	17	4.7	1.2	26	8.2	2.2	.548	20
1500	164	60	81	93	E/W	>50	>50	28	31	13	3.6	.875	14	4.1	1	.233	20
					North	>50	>50	29	35	13	3.6	.869	14	4.1	1	.232	11
4000	160	57	77	89	E/W	>50	43	20	23	9.4	2.8	.684	6.8	1.9	.44	.097	15
					North	>50	40	19	22	9	2.8	.68	6.5	1.9	.438	.097	8.5
KIGORIAK.1OKT																	
100	173	58	83	93	E/W	31	20	16	16	11	7.3	3.8	13	8.5	4.8	2.1	20
					North	>50	>50	>50	>50	33	12	4.4	46	16	6	2.2	20
200	168	60	84	95	E/W	37	22	16	17	11	6.3	2.6	13	8.2	3.8	1.3	20
					North	>50	>50	>50	>50	24	8.2	2.8	38	13	4.3	1.3	20
315	166	61	84	96	E/W	>50	37	24	25	14	6.2	1.8	19	9.2	3.2	.821	20
					North	>50	>50	>50	>50	24	6.8	1.8	36	12	3.3	.818	20
800	162	61	83	95	E/W	>50	46	18	22	8	2.1	.491	12	3.3	.788	.183	20
					North	>50	>50	21	27	8.1	2.1	.49	12	3.3	.783	.182	17

SITE = ORION (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= (km)	S:N= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	RLev Med+40 (km)	RLev 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	Max 130dB (km)	R Reli-able
LEMEUR.IOKT																		
40	169	56	82	91	E/W	>50	43	32	30	18	8.3	2.8	21	10	3.6	.725	10	
					North	>50	>50	>50	>50	27	9.3	2.8	33	11	3.6	.71	10	
100	164	58	83	93	E/W	21	16	12	12	7.7	4.2	1.7	8.9	5.2	2.2	.683	20	
					North	>50	>50	37	37	13	4.9	1.7	18	6.7	2.4	.681	20	
315	163	61	S4	96	E/W	>50	33	21	22	12	4.5	1.2	16	6.8	2.2	.535	20	
					North	>50	>50	43	49	16	4.6	1.2	28	8.1	2.2	.533	20	
LEMEUR.ICEBR																		
100	183	58	83	93	E/W	36	24	20	20	16	11	7.3	17	13	8.5	4.8	20	
					North	>50	>50	>50	>50	>50	33	12	>50	46	16	6	20	
250	182	60	84	95	E/W	>50	42	33	33	25	17	9.6	28	20	13	6	20	
					North	>50	>50	>50	>50	>50	44	14	>50	>50	22	7.5	20	
400	180	61	85	96	E/W	>50	>50	51	>50	36	21	9.1	44	28	14	4.8	20	
					North	>50	>50	>50	>50	>50	34	9.8	>50	>50	18	4.9	20	
2000	167	59	80	92	E/W	>50	>50	41	47	23	8.1	2.2	23	8.1	2.2	.504	19	
					North	>50	>50	45	51	23	7.9	2.1	23	7.9	2.1	.501	8.5	
4000	174	57	77	89	E/W	>50	>50	47	>50	30	14	4.7	25	11	3.2	.792	15	
					North	>50	>50	45	49	29	13	4.6	23	10	3.2	.786	8.5	
EXPL.II.DRILL																		
160	162	59	84	94	E/W	29	17	12	12	7.4	3.6	1.2	9	4.9	1.9	.52	20	
					North	>50	>50	32	33	12	3.9	1.2	17	5.9	2	.52	20	
315	160	61	84	96	E/W	>50	30	17	19	8.8	3.1	.776	13	5.3	1.4	.347	20	
					North	>50	>50	30	35	11	3.1	.773	19	5.5	1.4	.346	20	
SANDPIP.DRILL																		
40	145	56	82	91	E/W	46	14	6.5	5.8	1.8	.186	.025	2.3	.29	.03	.017	10	
					North	>50	18	6.8	6	1.7	.186	.025	2.3	.288	.03	-9	10	
ERIK.TUG.UNDERWAY																		
1000	164	60	82	94	E/W	>50	50	21	25	9.1	2.4	.573	12	3.2	.769	.179	20	
					North	>50	>50	23	29	9.1	2.4	.571	12	3.2	.765	.178	15	
2500	149	59	79	91	E/W	>50	26	7.8	9.9	2.8	.654	.154	2.5	.5B9	.138	.029	19	
					North	>50	26	7.5	9.5	2.7	.650	.153	2.5	.586	.138	.029	8.5	

Estimated ranges at which various noise levels would be received if one of nine industrial activities took place at the SANDPIPER site. For each industrial source, we consider the few 1/3-octave bands in which noise levels were highest relative to the median ambient noise level.

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli-able
ERIK. DREDGE																	
250	162	60	84	95	E/W	49	25	16	16	8.4	3.1	.811	12	4.8	1.5	.356	20
					North	>50	>50	29	31	10	3.2	.81	16	5.4	1.5	.355	20
750	158	61	84	96	E/W	>50	47	17	21	6.4	1.6	.368	10	2.6	.616	.142	20
					North	>50	>50	18	22	6.4	1.6	.367	10	2.6	.614	.141	20
1250	158	60	82	94	E/W	>50	>50	24	29	9.4	2.4	.555	11	3	.692	.162	20
					North	>50	>50	23	28	9.1	2.4	.553	11	2.9	.689	.161	19
ERIK. TUG & BARGE																	
1000	170	60	82	94	E/W	>50	>50	>50	>50	29	9.3	2.4	35	12	3.2	.74	20
					North	>50	>50	>50	>50	29	9.1	2.4	36	12	3.1	.736	20
3500	164	58	78	90	E/W	>50	>50	40	45	23	8.5	2.4	19	6.5	1.7	.395	16
					North	>50	>50	37	42	21	8.2	2.3	18	6.3	1.7	.394	16
SANDP.TUGS--Bollard condition																	
300	163	61	84	95	E/W	>50	32	19	20	9.8	3.5	.893	14	5.9	1.6	.392	20
					North	>50	>50	34	38	13	3.5	.891	19	6.2	1.6	.392	20
1500	164	60	81	93	E/W	>50	>50	48	>50	23	7.3	1.8	26	8.3	2.1	.483	20
					North	>50	>50	47	>50	23	7.1	1.8	25	8.1	2.1	.481	18
4000	160	57	7?	89	E/W	>50	>50	21	31	14	4.7	1.2	11	3.2	.772	.178	15
					North	>50	50	25	29	13	4.6	1.2	10	3.1	.768	.178	15
KIGORIAK.1OKT																	
100	173	58	83	93	E/W	38	24	18	18	13	8.3	4.1	15	9.7	5.3	2.2	20
					North	>50	>50	>50	>50	32	12	4.6	44	16	6.3	2.2	20
200	168	60	84	95	E/W	42	24	17	17	11	5.4	1.9	13	7.5	3.1	.858	20
					North	>50	>50	49	51	18	6	1.9	27	9.4	3.2	.857	20
315	166	6,1	84	96	E/W	>50	37	23	24	13	5	1.3	18	7.6	2.4	.599	20
					North	>50	>50	47	>50	18	5.1	1.3	28	9	2.4	.597	20
800	162	61	83	95	E/W	>50	>50	26	30	11	2.9	.678	16	4.5	1.1	.25	20
					North	>50	>50	28	35	11	2.9	.676	16	4.5	1.1	.249	20

SITE = SANDPIPER (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max Reliable
LEMEUR. 10KT																	
40	169	56	82	91	E/W	>50	43	32	30	18	8.3	2.8	21	10	3.6	.725	10
					North	>50	>50	>50	>50	25	8.9	2.8	31	11	3.6	.713	10
100	164	58	83	93	E/W	33	19	14	14	8.8	4.5	1.7	10	5.7	2.4	.738	20
					North	>50	>50	36	36	14	5.1	1.7	18	6.9	2.5	.733	20
315	163	61	84	96	E/W	>50	33	19	21	9.9	3.4	.872	14	5.9	1.6	.388	20
					North	>50	>50	33	38	13	3.5	.869	19	6.2	1.6	.387	20
LEMEUR. **ICEBR**																	
100	1s3	5s	83	93	E/W	43	29	24	24	18	13	8.3	20	15	9.7	5.3	20
					North	>50	>50	>50	>50	>50	32	12	>50	44	16	6.3	20
250	182	60	84	95	E/W	>50	45	34	35	25	16	8.4	29	20	12	4.s	20
					North	>50	>50		>50	>50	31	10	>50	50	16	5.4	20
400	180	61	85	96	E/W	>50	>50	50	>50	35	19	7.7	43	26	12	4	20
					North	>50	>50	>50	>50	>50	28	8.1	>50	48	15	4	20
2000	167	59	80	92	E/W	>50	>50	>50	>50	42	17	5	42	17	5	1.2	20
					North	>50	>50	>50	>50	40	16	4.9	40	16	4.9	1.2	17
4000	174	57	77	89	E/W	>50	>50	>50	>50	39	20	7.6	33	16	5.3	1.4	15
					North	>50	>50	>50	>50	37	19	7.3	31	15	5.2	1.4	15
EXPL . II . DRILL																	
160	162	59	84	94	E/W	34	19	13	13	7.5	3.3	.978	9.3	4.5	1.6	.4	20
					North	>50	>50	26	27	9.8	3.6	.979	14	5	1.6	.4	20
315	160	61	84	96	E/W	>50	29	16	17	7.3	2.3	.567	11	4.1	1.1	.253	20
					North	>50	>50	23	26	8.6	2.3	.566	15	4.2	1.1	.253	20
SANDPIP. DRILL																	
40	145	56	82	91	E/W	46	14	6.5	5.8	1.8	.186	.025	2.3	.29	.03	.017	10
					North	>50	17	6.8	6	1.8	.186	.025	2.3	.289	.03	-9	10
ERIK. TUG. UNDERWAY																	
1000	164	60	82	94	E/W	>50	>50	35	39	15	4.2	.993	19	5.5	1.3	.301	20
					North	>50	>50	36	43	15	4.1	.987	19	5.4	1.3	.300	20
2500	149	59	79	91	E/W	>50	43	15	18	5.8	1.4	.327	5.3	1.3	.293	.061	19
					North	>50	40	14	17	5.6	1.4	.326	5.1	1.3	.292	.060	17

Estimated ranges at which various noise levels would be received if one of nine industrial activities took place at the HAMMERHEAD site. For each industrial source, we consider the few 1/3-octave bands in which noise levels were highest relative to the median ambient noise level.

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli-able
ERIK. DREDGE																	
250	162	69	85	97	South	23	22	17	19	7.6	1.1	.106	14	3.3	.297	.04	20
					E/W	>50	>50	22	29	7.5	1	.106	14	2.9	.294	.04	20
					North	>50	>50	22	30	7.5	1	.106	14	2.8	.293	.04	20
750	158	69	S2	95	South	25	25	22	23	11	2.7	.258	15	3.5	.404	.046	20
					E/W	>50	>50	29	39	11	2.5	.256	14	3.5	.398	.046	20
					North	>50	>50	28	3?	11	2.4	.255	14	3.4	.395	.046	20
1250	158	67	82	94	South	25	25	24	24	16	3.9	.S85	19	5.1	1.2	.159	19
					E/W	>50	>50	37	45	15	3.9	.88	19	5	1.2	.158	19
					North	>50	>50	35	43	15	3.8	.87S	18	4.9	1.2	.15s	19
ERIK.TUG & BARGE																	
1000	170	67	82	94	South	26	25	25	25	25	18	4.5	25	21	6	1	20
					E/W	>50	>50	>50	>50	>50	17	4.4	>50	22	5.8	.9s7	20
					North	>50	>50	>50	>50	50	17	4.3	>50	21	5.7	.972	20
3500	164	63	81	93	South	26	26	25	25	24	12	3.5	25	13	4	.948	11
					E/W	>50	>50	47	>50	28	12	3.4	31	13	3.9	.943	11
					North	>50	>50	46	51	28	11	3.4	30	13	3.9	.941	11
SANDP.TUGS--Bollard condition																	
300	163	69	84	96	South	24	22	19	20	10	1.8	.179	16	5.3	.44	.047	20
					E/W	>50	>50	29	38	10	1,7	.178	18	4.3	.433	.047	20
					North	>50	>50	28	3S	9.9	1.7	.177	17	4	.43	.047	20
1500	164	66	82	94	South	26	25	25	25	23	12	2.8	24	14	3.5	.791	18
					E/W	>50	>50	>50	>50	34	11	2.8	39	13	3.5	.788	18
					North	>50	>50	>50	>50	33	11	2.8	38	13	3.4	.786	18
4000	160	62	81	93	South	26	26	25	25	19	6.7	1.8	20	7.6	2	.47	10
					E/W	>50	>50	33	37	18	6.5	1.8	20	7.3	2	.469	10
					North	>50	>50	32	36	18	6.5	1.8	19	7.2	2	.469	10

SITE = HAMMERHEAD (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli-able
KIGORIAK.1OKT																	
63	173	67	90	100	South	17	14	12	12	8,8	5.1	.494	12	8.9	5.1	.518	13
					E/W	>50	36	24	23	12	4.8	.485	23	12	5.1	.507	13
					North	>50	>50	34	32	13	4.5	.482	33	13	4.7	.503	13
100	173	68	88	98	South	19	17	16	16	13	7.2	1.7	15	12	6.8	1	20
					E/W	>50	>50	40	40	21	7.9	1.6	36	18	6.2	1	20
					North	>50	>50	>50	>50	25	8.1	1.6	>50	20	6.2	.986	20
200	168	69	85	97	South	23	22	19	20	14	3.6	.323	18	7.9	1	.101	20
					E/W	>50	>50	41	>50	15	3.2	.319	29	7.5	1	.1	20
					North	>50	>50	43	>50	15	3	.317	29	7.4	.985	.1	20
315	166	69	84	96	South	24	23	21	22	15	4.3	.374	19	6.8	.93	.09	20
					E/W	>50	>50	43	>50	16	3.6	.369	27	6.7	.898	.09	20
					North	>50	>50	43	>50	16	3.4	.367	26	6.6	.885	.09	20
800	162	68	82	94	South	25	25	24	24	19	5	.706	22	6.6	1.1	.114	20
					E/W	>50	>50	47	>50	19	4.8	.688	25	6.5	1.1	.113	20
					North	>50	>50	45	>50	19	4.8	.681	24	6.4	1.1	.113	20
LEMEUR.1OKT																	
40	169	67	91	100	South	11	9.9	7.9	7.7	4.7	1.3	.134	7.9	5	1.7	.168	10
					E/W	33	17	11	11	5.2	1.3	.134	11	5.7	1.6	.167	10
					North	>50	24	13	12	5.5	1.2	.133	13	6	1.6	.166	10
100	164	68	88	98	South	19	16	13	13	7.5	2.2	.202	12	6.9	1.3	.134	20
					E/W	>50	42	23	23	9	2	.2	19	7	1.3	.134	20
					North	>50	>50	27	21	9.2	1.9	.199	22	7.1	1.2	.133	20
315	163	69	84	96	South	24	23	20	21	11	2	.189	16	5.5	.461	.048	20
					E/W	>50	>50	30	40	10	1.8	.188	18	4.4	.453	.048	20
					North	>50	>50	29	39	10	1.8	.187	18	4.2	.45	.048	20

SITE = HAMMERHEAD (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli-able
LEMEUR.ICEBR																	
100	183	68	S8	9s	South	20	18	17	17	16	13	7.2	17	15	12	6.S	20
					E/W	>50	>50	>50	>50	40	21	7.9	>50	36	18	6.2	20
					North	>50	>50	>50	>50	>50	25	8.1	>50	>50	20	6.2	20
250	182	69	85	97	South	24	23	23	23	22	19	7.6	22	20	14	3.3	20
					E/W	>50	>50	>50	>50	>50	29	7.5	>50	51	14	2.9	20
					North	>50	>50	>50	>50	>50	30	7.5	>50	>50	14	2.s	20
400	1S0	70	83	96	South	25	25	24	24	23	21	S.9	23	22	13	3.3	20
					E/W	>50	>50	>50	>50	>50	34	8.7	>50	49	13	2.9	20
					North	>50	>50	>50	>50	>50	33	8.6	>50	48	13	2.8	20
2000	167	65	81	93	South	26	25	25	25	25	22	7.4	25	22	8.5	2.1	15
					E/W	>50	>50	>50	>50	>50	23	7.2	>50	26	8.2	2.1	15
					North	>50	>50	>50	>50	>50	23	7.1	>50	25	S.1	2	15
4000	174	62	81	93	South	26	26	26	26	26	24	11	26	24	12	3.5	10
					E/W	>50	>50	>50	>50	46	25	10	4s	27	11	3.5	10
					North	>50	>50	>50	>50	45	24	10	47	26	11	3.5	10
EXPL.II.DRILL																	
63	167	67	90	100	South	17	13	11	10	5.s	1.3	.129	11	5.9	1.3	.136	13
					E/W	>50	28	17	16	6.9	1.2	.128	16	6.9	1.3	.135	13
					North	>50	45	20	19	8.2	1.2	.12s	19	S.2	1.2	.135	13
160	162	69	86	97	South	21	19	15	16	7.4	.992	.096	13	4.s	.405	.046	20
					E/W	>50	>50	22	25	6.9	.957	.096	16	4	.399	.046	20
					North	>50	>50	23	26	6.9	.942	.096	16	3.7	.397	.046	20
315	160	69	84	96	south	23	22	18	19	6.9	.953	.092	12	2.5	.232	.034	20
					E/W	>50	>50	20	27	6.S	.919	.092	12	2.3	.23	.034	20
					North	>50	>50	20	27	6.7	.905	.092	12	2.2	.229	.034	20
SANDPIP.DRILL																	
40	145	67	91	100	South	9.9	3.4	.649	.513	.05	.01s	-9	.649	.064	.02	-9	10
					E/W	17	3.5	.634	.502	.05	.018	-9	.634	.064	.02	-9	10
					North	24	3.8	.627	.49s	.05	.018	-9	.627	.064	.02	-9	10

SITE = HAMMERHEAD (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dirtn from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli- able
ERIK.TUG.UNDERWAY																	
1000	164	67	82	94	South	26	25	25	25	23	8.o	1,7	23	11	2.6	.258	20
					E/W	>50	>50	>50	>50	28	7.7	1.6	35	10	2.4	.256	20
					North	>50	>50	>50	>50	27	7.6	1.5	33	9.9	2.3	.255	20
2500	149	64	81	93	South	26	25	20	23	8.5	2.1	.4S2	9.7	2.5	.560	.129	14
					E/W	>50	>50	20	25	8.2	2,1	.480	9.3	2.4	.559	.12s	14
					North	>50	51	20	24	8.1	2.1	.480	9.2	2.4	..558	.12s	14

Estimated ranges at which various noise levels would be received if one of nine industrial activities took place at the CORONA site. For each industrial source, we consider the few 1/3-octave bands in which noise levels were highest relative to the median ambient noise level.

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli- able
ERIK. DREDGE																	
250	162	69	85	97	South	24	20	12	14	5	1.2	.186	8.9	2.4	.517	.051	30
					E/W	>50	42	14	18	5.1	1.2	.185	9.2	2.4	.509	.051	30
					North	>50	>50	14	19	5.1	1.2	.185	9.3	2.3	.502	.051	20
750	158	69	82	95	South	29	27	16	20	6.1	1.4	.312	8	1.9	.422	.091	30
					E/W	>50	>50	16	22	6	1.4	.311	7.9	1.9	.421	.091	25
					North	>50	>50	16	22	5.9	1.4	.311	7.8	1.9	.42	.091	15
1250	158	67	82	94	South	32	30	22	26	8.7	2.1	.464	11	2.7	.607	.14	28
					E/W	>50	>50	23	29	8.5	2.1	.463	11	2.7	.605	.14	23
					North	>50	>50	22	27	8.3	2	.462	11	2.7	.604	.14	14
ERIK.TUG & BARGE																	
1000	170	67	82	94	South	31	31	29	29	24	7.9	1.9	26	10	2.5	.563	30
					E/W	>50	>50	>50	>50	27	7.8	1.9	34	10	2.5	.562	23
					North	>50	>50	>50	>50	26	7.6	1.9	33	9.9	2.5	.56	14
3500	164	63	81	93	South	34	33	32	32	21	7.4	1.9	23	8.4	2.2	.508	20
					E/W	>50	>50	37	42	20	7.2	1.9	22	8.1	2.2	.506	20
					North	>50	>50	35	40	20	7	1.9	21	7.9	2.2	.505	13
SANDP.TUGS--Bollard condition																	
300	163	69	84	96	South	25	22	14	17	6.7	1.6	.369	11	2.9	.674	.091	30
					E/W	>50	>50	18	24	6.7	1.6	.366	11	2.9	.672	.091	30
					North	>50	>50	19	25	6.7	1.6	.362	12	2.9	.671	.091	19
1500	164	66	82	94	South	32	32	30	31	24	7.3	1.8	26	9	2.2	.485	25
					E/W	>50	>50	52	>50	24	7.2	1.7	28	8.8	2.2	.484	23
					North	>50	>50	48	>50	23	7	1.7	27	8.5	2.1	.483	14
4000	160	62	81	93	South	34	33	24	28	12	3.5	.848	13	4	.982	.222	20
					E/W	>50	48	23	27	11	3.5	.844	13	4	.978	.221	20
					North	>50	46	22	26	11	3.4	.841	12	3.9	.974	.221	13

SITE CORONA (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= Med Amb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli- able
KIGORIAK. 10KT																	
63	173	67	90	100	South	15	11	8.3	8.1	5.1	2.5	.252	8.2	5.2	2.6	.264	23
					E/W	30	16	11	11	5.7	2.5	.25	11	5.8	2.5	.262	23
					North	>50	30	15	14	6.3	2.3	.249	15	6.4	2.4	.26	23
100	173	68	88	98	South	19	15	12	12	8.2	4.7	.583	12	7.2	4.1	.368	28
					E/W	>50	29	19	19	9.9	4.6	.574	17	8.3	3.6	.365	30
					North	>50	>50	31	31	11	4.2	.565	26	9.1	3.3	.361	29
200	168	69	85	97	South	23	20	15	16	9	2.5	.438	13	5	1*3	.145	30
					E/W	>50	49	21	25	9.6	2.5	.433	16	5	1.3	.145	30
					North	>50	>50	27	35	9.8	2.5	.427	19	5	1.3	.144	22
315	166	69	84	96	South	26	23	18	19	10	2.6	.6	14	4.6	1.1	.202	30
					E/W	>50	>50	26	31	10	2.6	.599	17	4.5	1.1	.201	30
					North	>50	>50	28	38	10	2.6	.598	18	4.5	1.1	.199	19
800	162	68	82	94	South	30	28	22	25	11	2.5	.569	14	3.4	.769	.175	30
					E/W	>50	>50	27	35	10	2.5	.568	14	3.4	.767	.175	25
					North	>50	>50	26	34	10	2.5	.567	13	3.3	.764	.175	14
LEMEUR.1OKT																	
40	169	67	91	100	South	9.2	5.9	4.4	4.3	2.5	.738	.081	4.4	2.7	.933	.091	17
					E/W	14	7.4	5.1	4.8	2.6	.722	.081	5.1	2.8	.908	.091	20
					North	28	9.5	5.9	5.6	2.7	.707	.081	5.9	3	.886	.091	20
100	164	68	88	98	South	17	13	8.7	S.7	4.8	.738	.081	7.7	4.6	.463	.064	28
					E/W	41	20	11	11	4.8	.722	.081	9.1	4.5	.458	.064	30
					North	>50	34	13	13	4.4	.707	.081	10	4	.452	.064	29
315	163	69	84	96	South	25	22	15	17	6.9	1.7	.382	11	3	.6S7	.101	30
					E/W	>50	>50	19	25	7	1.7	.382	12	3	.686	.101	30
					North	>50	>50	19	26	6.9	1.7	.381	12	3	.684	.1	19

SITE = CORONA (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli- able
LEMEUR.ICEBR																	
100	183	68	88	98	South	20	17	15	15	12	8.2	4.7	15	12	7.2	4.1	28
					E/W	>50	40	29	29	19	9.9	4.6	27	17	8.3	3.6	30
					North	>50	>50	>50	>50	31	11	4.2	>50	26	9.1	3.3	29
250	182	69	85	97	South	26	24	22	23	20	14	5	21	17	8.9	2.4	30
					E/W	>50	>50	>50	>50	42	18	5.1	>50	27	9.2	2.4	30
					North	>50	>50	>50	>50	>50	19	5.1	>50	34	9.3	2.3	20
400	180	70	83	96	South	28	27	25	26	23	17	5.9	24	20	8.8	2.2	30
					E/W	>50	>50	>50	>50	>50	22	5.9	>50	31	8.9	2.2	30
					North	>50	>50	>50	>50	>50	22	5.9	>50	33	8.9	2.2	17
2000	167	65	81	93	South	33	33	32	32	31	20	5.9	31	22	6.8	1.6	20
					E/W	>50	>50	>50	>50	48	20	5.8	>50	22	6.6	1.6	20
					North	>50	>50	>50	>50	45	19	5.6	49	21	6.4	1.6	14
4000	174	62	81	93	South	34	34	33	33	32	17	5.9	32	19	6.7	1.8	20
					E/W	>50	>50	>50	>50	35	17	5.8	37	18	6.5	1.8	20
					North	>50	>50	51	>50	33	16	5.7	35	18	6.4	1.7	13
EXPL.II.DRILL																	
63	167	67	90	100	South	14	9.2	6.6	6.4	3.2	.629	.074	6.4	3.2	.66	.076	23
					E/W	26	13	7.9	7.5	3.3	.617	.074	7.6	3.3	.647	.076	23
					North	>50	19	9.5	8.9	3.4	.606	.074	9.1	3.5	.636	.076	23
160	162	69	86	97	South	21	16	9.5	10	3.9	.797	.079	7'.8	2.4	.331	.047	30
					E/W	>50	28	11	12	3.9	.78	.079	8.7	2.4	.328	.047	30
					North	>50	44	13	15	4	.764	.078	9	2.4	.324	.047	25
315	160	69	84	96	South	25	21	12	14	4.6	1.1	.208	7.8	1.9	.441	.051	30
					E/W	>50	45	13	17	4.6	1.1	.206	7.9	1.9	.44	,05	30
					North	>50	>50	13	18	4.6	1.1	,205	7.9	1.9	.439	.05	19
SANDPIP.DRILL																	
40	145	67	91	100	South	5.9	1.8	.368	.291	.05	.018	-9	.368	.057	.02	-9	17
					E/W	7.4	1.8	.365	.289	.05	.018	-9	.365	.057	.02	-9	20
					North	9.5	1.9	.361	.287	.05	.018	-9	.361	.057	.02	-9	20

SITE = CORONA (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max Reli-able
ERIK.TUG.UNDERWAY																	
1000	164	67	82	94	South	31	30	26	27	14	3.4	.761	17	4.5	1.0	.229	30
					E/W	>50	>50	34	42	13	3.3	.758	17	4.4	1.0	.229	23
					North	>50	>50	33	40	13	3.3	.756	17	4.4	1.0	.229	14
2500	149	64	81	93	South	33	32	16	20	6.1	1.5	.331	7	1.7	.384	.081	20
					E/W	>50	45	16	19	6.0	1.5	.331	6.8	1.7	.383	.081	20
					North	>50	43	15	19	5.9	1.5	.330	6.7	1.7	.383	.081	14

Estimated ranges at which various noise levels **would be received if one of nine industrial activities took place at the** ERIK site. For each industrial source, we consider the few 1/3-octave banda in which noise levels were highest relative to the median ambient noise level.

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli-able
ERIK. DREDGE																	
250	162	69	85	97	South	22	20	13	16	4.7	.687	.069	8.9	2	.193	.037	25
					E/W	>50	>50	14	19	4.6	.671	.069	8.8	1.9	.192	.037	40
					North	>50	>50	14	19	4.6	.659	.069	8.7	1.8	.191	.037	34
750	158	69	82	95	South	24	22	8	11	2.7	.383	.05	3.6	.607	.065	.023	26
					E/W	>50	39	7.8	11	2.6	.378	.05	3.5	.594	.065	.023	40
					North	>50	37	7.6	11	2.6	.374	.05	3.5	.585	.065	.023	22
1250	158	61	82	94	South	25	23	7.8	10	2.4	.357	.049	3.2	.54	.061	.022	26
					E/W	>50	32	7.5	9.8	2.4	.353	.049	3.1	.528	.061	.022	40
					North	>50	31	7.3	9.5	2.4	.349	.049	3.1	.521	.061	.022	20
ERIK.TUG & BARGE																	
1000	170	67	82	9.4	South	25	25	23	23	12	2.9	.481	16	3.9	.766	.076	26
					E/W	>50	>50	32	39	12	2.9	.473	15	3.9	.745	.076	40
					North	>50	>50	30	37	11	2.9	.467	15	3.8	.73	.075	20
3500	164	63	81	93	South	26	25	13	16	4.7	1.2	.125	5.4	1.3	.158	.032	25
					E/W	>50	34	12	15	4.6	1.1	.124	5.3	1.3	.157	.032	25
					North	>50	32	12	14	4.5	1.1	.124	5.2	1.3	.157	.032	20
SANDP.TUGS--Bollard condition																	
300	163	69	84	96	South	23	21	15	17	5.7	.98	.095	9.9	2.5	.245	.041	25
					E/W	>50	>50	16	22	5.6	.945	.095	9.9	2.4	.242	.041	40
					North	>50	>50	16	22	5.5	.921	.095	9.7	2.2	.241	.041	31
1500	164	66	82	94	South	25	25	18	22	6.5	1.5	.175	8	1.9	.243	.041	26
					E/W	>50	>50	18	22	6.3	1.5	.175	7.7	1.9	.241	.041	40
					North	>50	>50	17	21	6.1	1.5	.174	7.5	1.8	.24	.041	20
4000	160	62	81	93	South	26	23	6.7	8.5	2.3	.376	.05	2.7	.471	.057	.02	20
					E/W	>50	21	6.5	8.2	2.3	.371	.05	2.6	.463	.057	.02	20
					North	>50	21	6.4	8	2.3	.367	.05	2.6	.458	.057	.02	19

SITE = **ERIK** (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli- able
KIGORIAK. 10KT																	
63	173	67	90	100	South	18	15	13	13	8.2	2.9	.694	13	8.3	3	.729	19
					E/W	>50	41	24	23	10	2.9	.677	24	10	3	.708	25
					North	>50	>50	36	33	11	2.9	.665	34	11	3	.695	25
100	173	68	88	98	South	20	17	15	15	9.2	3	.698	14	8.2	2.2	.514	22
					E/W	>50	>50	29	29	11	3	.696	25	8.7	2.2	.504	40
					North	>50	>50	41	41	12	3	.695	32	8.8	2.2	.497	40
200	168	69	85	97	South	22	21	17	18	10	2.6	.245	15	5.2	.774	.076	23
					E/W	>50	>50	30	38	10	2.4	.243	20	5.2	.752	.076	40
					North	>50	>50	30	39	10	2.2	.241	20	5.1	.737	.076	37
315	166	69	84	96	South	23	22	18	19	8.7	2.1	.196	14	3.6	.484	.058	25
					E/W	>50	>50	25	33	8.6	1.9	.195	15	3.6	.476	.058	40
					North	>50	>50	24	33	8.4	1.8	.194	15	3.5	.47		31
800	162	68	82	94	South	25	23	14	18	4.6	.927	.091	6.2	1,4	.152	.031	26
					E/W	>50	>50	13	18	4.5	.894	.09	6	1.4	.152	.031	40
					North	>50	>50	13	17	4.5	.874	.09	5.9	1.4	.151	.031	22
LEMEUR. 10KT																	
40	169	67	91	100	South	15	11	8.9	8.6	4.7	1.6	.26	8.9	5.2	1.8	.324	15
					E/W	45	21	13	12	5.1	1.6	.257	13	5.7	1.8	.32	20
					North	>50	39	17	15	5.8	1.6	.256	17	6.2	1.8	.317	20
100	164	68	88	98	South	19	15	10	10	3.4	.808	.101	8.7	2.6	.625	.064	22
					E/W	>50	32	13	13	3.4	.806	.101	9.9	2.6	.618	.064	40
					North	>50	47	13	13	3.4	.804	.1	10	2.6	.613	.064	40
315	163	69	84	96	South	23	21	15	17	5.7	1	.097	9.8	2.5	.245	.041	25
					E/W	>50	>50	17	23	5.6	.967	.097	9.8	2.4	.242	.041	'40
					North	>50	>50	16	22	5.5	.942	.097	9.6	2.2	.241	.041	31

SITE = ERIK (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli-able
LEMEUR.ICEBR																	
100	183	68	88	98	South	20	19	17	17	15	9.2	3	17	14	8.2	2.2	22
					E/W	>50	>50	>50	>50	29	11	3	51	25	8.7	2.2	40
					North	>50	>50	>50	>50	41	12	3	>50	32	8.8	2.2	40
250	1s2	69	85	97	South	23	22	22	22	20	16	4.7	21	19	8.9	2	25
					E/W	>50	>50	>50	>50	>50	19	4.6	>50	34	8.8	1.9	40
					North	>50	>50	>50	>50	>50	19	4.6	>50	34	8.7	1.8	34
400	180	70	83	96	South	24	23	23	23	22	16	4	22	19	6.2	1.2	25
					E/W	>50	>50	>50	>50	>50	16	3.9	>50	24	6.1	1.2	40
					North	>50	>50	>50	>50	>50	16	3.9	>50	24	6	1.2	28
2000	167	65	81	93	South	25	25	24	25	12	2.9	.478	13	3.4	.6	.065	26
					E/W	>50	>50	27	32	11	2.9	.47	12	3.3	.587	.065	40
					North	>50	>50	25	30	11	2.8	.464	12	3.3	.579	.065	20
4000	174	62	81	93	South	26	26	25	25	13	4	.924	15	4.6	1.1	.125	20
					E/W	>50	51	25	29	13	3.9	.894	14	4.5	1.1	.124	20
					North	>50	48	24	28	12	3.9	.874	13	4.4	1.1	.124	19
EXPL.II.DRILL																	
63	167	67	90	100	South	18	14	11	10	4.s	1.3	.177	11	4.9	1.3	.184	19
					E/W	>50	30	15	14	4.9	1.3	.176	15	5.1	1.3	.183	25
					North	>50	>50	18	18	5	1.2	.176	18	5.1	1.3	.182	25
160	162	69	86	97	South	21	18	11	13	3.6	.707	.069	8.4	2.1	.292	.036	23
					E/W	>50	43	12	14	3.6	.689	.069	8.6	2.1	.289	.036	40
					North	>50	>50	12	14	3.6	.677	.069	8.6	2.1	.287	.036	38
315	160	69	84	96	South	23	21	11	14	3.7	.494	.058	6.5	1.2	.126	.029	25
					E/W	>50	>50	11	15	3.6	.486	.058	6.4	1.2	.125	.029	40
					North	>50	>50	11	15	3.6	.4s	.058	6.3	1.2	.125	.029	31
SANDPIP.DRILL																	
40	145	67	91	100	South	11	3.4	1.2	1	.101	.019	-9	1.2	.135	.021	-9	15
					E/W	21	3.5	1.2	1	.101	,019	-9	1.2	.134	.021	-9	20
					North	39	3.5	1.2	,979	.1	,019	-9	1.2	.133	.021	-9	20

SITE = ERIK (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= Med (km)	RLev= Amb (km)	S:N= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	RLev= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB RLev= 120dB (km)	RLev= 130dB (km)	Max R Reli- able
ERIK.TUG.UNDERWAY																	
1000	164	67	82	94	South	25	24	16	20	5.3	1.2	.126	7.1	1.6	.192	.037	26
					E/W	>50	>50	15	20	5.2	1.2	.125	6.8	1.6	.191	.037	40
					North	>50	>50	15	19	5.1	1.1	.124	6.7	1.6	.191	.037	20
2500	149	64	81	93	South	25	13	2.5	3.3	.597	.065	.023	.753	.076	.025	-9	26
					E/W	>50	12	2.4	3.2	.585	.065	.023	.732	.075	.025	-9	35
					North	50	12	2.4	3.2	.577	.065	.023	.718	.075	.025	-9	20

Estimated ranges at which various noise levels would be received if one of nine industrial activities took place at the BELCHER site. For each industrial source, we consider the few 1/3-octave bands in which noise levels were highest relative to the median ambient noise level.

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max Reliable
ERIK.DREDGE																	
250	162	69	S5	97	E/W	>50	>50	25	33	8.1	1.2	.121	16	3.2	.328	.057	50
					South	37	35	24	29	8.3	1.2	.121	16	3.5	.331	.057	40
750	158	69	82	95	E/W	>50	>50	12	17	3.9	.405	.067	5.4	.641	.085	.028	50
					South	40	38	12	18	4.3	.409	.067	5.5	.651	.085	.028	41
1250	158	67	82	94	E/W	>50	38	9	12	2.9	.35	.055	3.7	.524	.067	.024	48
					South	40	37	9.2	12	2.9	.353	.055	3.8	.531	.067	.024	41
ERIK.TUG & BARGE																	
1000	170	67	82	94	E/W	>50	>50	38	47	14	3.5	,434	19	4.7	.682	.08	50
					South	40	40	36	38	15	3.6	.438	20	4.8	.693	. 0s	41
3500	164	63	81	93	E/W	>50	29	9.4	12	3.4	.576	.071	3.9	.718	.081	.027	18
					South	41	31	9.7	12	3.5	.583	.071	4	.73	.081	.027	18
SANDP.TUGS--Bollard condition																	
300	163	69	84	96	E/W	>50	>50	30	41	10	1.5	.164	18	3.8	.388	.064	50
					South	38	36	28	31	10	1.6	.164	18	4.2	.391	.064	40
1500	164	66	82	94	E/W	>50	>50	20	26	7.4	1.7	.184	9.1	2.2	.257	.046	45
					South	41	40	22	27	7.6	1.7	.185	9.4	2.2	.259	.046	41
4000	160	62	81	93	E/W	>50	16	4.3	5.6	1.3	.144	.037	1.6	.177	.041	.014	10
					South	41	17	4.4	5.7	1.3	.145	.037	1.6	.178	.041	.014	10
KIGORIAK.1OKT																	
63	173	67	90	100	E/W	>50	51	32	30	14	4.4	1.1	31	14	4.5	1.1	28
					South	26	22	18	18	12	4.4	1.1	18	12	4.5	1.1	28
100	173	68	88	98	E/W	>50	>50	4S	48	21	5.9	1.4	42	17	4.5	1.1	50
					south	30	27	23	23	16	5.9	1.4	22	14	4.5	1.1	37
200	168	69	85	97	E/W	>50	>50	>50	>50	18	4.3	,437	35	8.7	1.4	.146	50
					South	37	35	30	32	18	4.9	.441	27	8.9	1.4	.146	40
315	166	69	S4	96	E/W	>50	>50	45	>50	16	3.1	.309	27	6.5	.757	.089	50
					South	38	37	32	34	16	3.3	.312	26	6.6	.77	.0s9	40
800	162	68	82	94	E/W	>50	>50	19	26	6.6	.936	.1	8.8	1.5	.161	.041	50
					south	40	39	20	27	6.8	.957	.1	9.1	1.5	.162	.041	41

SITE = BELCHER (continued)

Freq (Hz)	1/3 OB S Lev (dB)	5% Ambi (dB)	Median Ambi (dB)	95% Ambi (dB)	Dir'n from Site	RLev= 5%Amb (km)	RLev= MedAmb (km)	RLev= 95%Amb (km)	S:N= Med+10 (km)	S:N= Med+20 (km)	S:N= Med+30 (km)	S:N= Med+40 (km)	RLev= 100dB (km)	RLev= 110dB (km)	RLev= 120dB (km)	RLev= 130dB (km)	Max Reliable
LEMEUR.1OKT																	
40	169	67	91	100	E/W	49	24	15	14	6.6	2.2	.582	15	7.3	2.5	.652	20
					South	20	15	11	11	6.1	2.2	.589	11	6.6	2.5	.654	20
100	164	68	88	98	E/W	>50	>50	22	22	6.8	1.7	.369	19	5.1	1.2	.236	50
					South	29	24	17	17	6.7	1.7	.372	15	5.1	1.2	.237	37
315	163	69	84	96	E/W	>50	>50	30	41	10	1.5	.165	18	3.8	.381	.064	50
					South	38	37	28	32	10	1.6	.166	18	4.2	.3s4	.064	40
LEMEUR.ICEBR																	
100	183	68	88	98	E/W	>50	>50	>50	>50	48	21	5.9	>50	42	17	4.5	50
					South	31	29	27	27	23	16	5.9	26	22	14	4.5	37
250	182	69	85	97	E/W	>50	>50	>50	>50	>50	33	8.1	>50	>50	16	3.2	50
					South	38	37	36	37	35	29	8.3	36	33	16	3.5	40
400	180	70	83	96	E/W	>50	>50	>50	>50	>50	30	7.4	>50	45	11	1.7	50
					South	40	39	38	38	37	29	7.5	3S	34	12	1.8	40
2000	167	65	81	93	E/W	>50	>50	30	36	13	3.3	.571	14	3.s	.714	.073	40
					South	41	41	32	37	13	3.4	.578	15	3.9	.727	.073	40
4000	174	62	81	93	E/W	>50	43	19	23	8.9	2.5	.341	9.9	2.9	.425	.064	10
					South	41	40	20	24	9.1	2.6	.344	10	2.9	.429	.064	10
EXPL.II.DRILL																	
63	167	67	90	100	E/W	>50	38	21	20	7.4	1.9	.443	20	7.6	2	.463	28
					South	26	20	15	15	1.2	1.9	.448	15	7.3	2	.46S	28
160	162	69	S6	97	E/W	>50	>50	22	26	6.5	1.5	.173	16	3.8	.691	.069	50
					South	34	30	20	22	6.6	1.5	.174	15	3.8	.702	.069	38
315	160	69	84	96	E/W	>50	>50	20	27	6.6	.774	.09	12	1.9	.193	.046	50
					South	38	36	20	27	6.7	.788	.09	12	2	.194	.046	40
SANDPIP.DRILL																	
40	145	67	91	100	E/W	24	4.6	1.5	1.3	.236	.029	-9	1.5	.292	.033	-9	20
					South	15	4.3	1.5	1.3	.237	.029	-9	1.5	.294	.033	-9	20
ERIK.TUG.UNDERWAY																	
1000	164	67	82	94	E/W	>50	>50	19	24	6.3	1.1	.112	8.4	1.7	.179	.041	50
					South	40	39	20	25	6.5	1.1	.113	8.6	1.8	.179	.041	41
2500	149	64	81	93	E/W	>50	12	2.4	3.2	.534	,064	.023	.668	.071	.025	-9	33
					South	40	12	2.4	3.2	.541	.064	.023	.678	.071	.025	-9	33

APPENDIX E

ZONE OF INFLUENCE LOOKUP TABLES FOR VARIOUS SITES, SOURCE LEVELS, AND FREQUENCIES

APPENDIX E: ZONE OF INFLUENCE LOOKUP TABLES FOR VARIOUS SITES, SOURCE LEVELS, AND FREQUENCIES*

This appendix tabulates, for various source levels and frequencies of continuous industrial noise, the ranges (in kilometers) within which whales might be influenced by the noise. The tables allow one to look up the expected zone of influence of industrial souces whose dominant noise components differ in frequency or intensity from those studied in this project. To use these tables, one needs to know the source level (in dB re 1 μPa at 1 m) in one or more l/3-octave bands with maximum level and/or maximum signal to ambient noise ratio.

It is emphasized that these tables apply only to continuous industrial noise, not impulsive sounds.

These tables assume constant water depth, i.e. propagation to the east or west of the industrial site along an isobath. Results would differ for propagation into shallower or deeper water. Similar tables for northward and southward propagation are available from the author.

There are two tables for each site, one based on the signal-to-noise (S:N) ratio criterion under median ambient noise conditions, and one based on the absolute received level (RL) criterion. These tables are based on the Weston/Smith shallow-water sound propagation models developed by BBN and implemented by LGL. The parameters used in the propagation model for each frequency are given near the top of each table.

The S:N tables give the ranges at which the “signal-to-noise ratio would be expected to be O, 10, 20, 30 and 40 dB. The expected maximum range of audibility is the range where S:N =

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*By W.J. Richardson, LGL Ltd.

O dB. The expected range within which some whales might respond overtly is the range where S:N = 20 or 30 dB. To look up the range where S:N would be 30 dB under median ambient conditions, look in the S:N = 30 dB column (col. 4) and find the source level of the sound. Look across this row to the column that pertains to the frequency of that sound, and read off the range (in km) where S:N would be expected to be 30 dB. For example, at Orion (first table), for SL = 160 dB re 1 uPa in the l/3-octave band centered at 1000 Hz, S:N would be 30 dB at a range of about 1.4 km and 20 dB at 5.5 km.

The RL tables give the ranges at which the absolute received level of industrial noise would be expected to be 90, 100, 110, 120, and 130 dB re 1 μPa. The expected range within which whales might respond overtly is the range where RL = 110 dB. The lookup procedure in the RL tables is similar to that in the S:N tables. For example, at Orion (second table), for SL = 160 dB re 1 μPa in the l/3-octave band centered at 1000 Hz, RL would be 110 dB at a range of about 1.8 km.

'Zone of influence' vs. source level and frequency for site ORION,
based on various SIGNAL-TO-NOISE RATIO criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m) 14 (effective depth 35 mfor 50Hz)
Bottom Slope (-1 to 1) 0
Sound Speed (m/s) 7435
Max. Range (km) 50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	3	5	8	4	0	6	2
Sine (Crit.Ang.) (0-1)	.8	.8	.8	.8	.8	.8	.8
Bottom Refl. 'B' (0-5)	.04	.05	.15	.2	.5	1.2	1.2
Median Ambient (dB)	82	83	84	85	82	80	77
Max. R with Data (km)	10	20	20	20	20	20	15
Max.R for spher.spr.(km)	.01	.007	.007	.007	.007	.007	.007
Max.R for cylin.spr.(km)	2	.6	.2	.1	.05	.01	.01
Max.R for multimode (km)	10		2.5	13	20	35	50+
Max.R for reliable values	50+	50+	50+	50+	44	18.5	18.5

SL (dB) when S:N (dB) =

0	10	20	30	40	50	100	200	500	1000	2000	4000
185	195	205	215	225	50+?	25?	32?	50+?	50+?	50+?	50+?
180	190	200	210	220	50+?	23?	29?	50+?	50+?	50+?	50+?
175	185	195	205	215	50+?	21?	26?	50+?	50+?	50+?	50+?
170	180	190	200	210	50+?	19	23?	50+?	50+?	50+?	50+?
165	175	185	195	205	50+?	16	21?	50+?	50+?	50+?	50+?
160	170	180	190	200	44?	14	18	41?	39?	50+?	43?
155	165	175	185	195	34?	12	15	31?	27?	41?	32?
150	160	170	180	190	25?	10	12	21?	18	30?	23?
145	155	165	175	185	17?	8.1	9.6	13	10	19?	15
140	150	16o	170	180	11?	6.2	7.2	7.9	5.5	11	9.4
135	145	155	165	175	6.4	4.5	5.0	4.1	2.8	6.3	5.3
13o	140	150	160	170	3.3	2.9	3.1	2.1		3.3	2.8
125	135	145	155	165	1.8	1.9	1.9	1.0	. x	1.6	1.4
120	130	140	150	160	.577	.993	.980	.488	.317	.786	.684
115	125	135	145	155	.186	.574	.492	.235	.157	.376	.327
110	120	130	140	150	.058	.186	.250	.091	.069	.182	.161
105	115	125	135	145	.025	.058	.091	.029	.025	.083	.071
-1oo	110	120	130	140	.012	.021	.029	.009	.008	,040	.034
95	105	115	125	135	.006	.007	.009	.005	.005	.016	.012
90	100	110	120	130	.004	.004	,005	.003	.003	.006	.006

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' vs. source level and frequency for site ORION,
based on various RECEIVED LEVEL criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m) 14 (effective depth 35 m for 50 Hz)
Bottom Slope (-1 to 1) 0
Sound Speed (m/s) 1435
Max. Range (km) 50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	3	5	8	4	0	6	2
Sine (Crit.Ang.) (0-1)	.8	.8	.8	.8	.8	.8	.8
Bottom Refl. 'B' (0-5)	.04	.05	.15	.2	.5	1.2	1.2
Median Ambient (dB)	82	83	84	85	82	80	77
Max. R with Data (km)	10	20	20	20	20	20	15
Max.R for spher.spr. (km)	.01	.007	.007	.007	.007	.007	.007
Max.R for cylin.spr. (km)	2	.6	.2	.1	.05	.01	.01
Max.R for multimode (km)	10	2	2.5	13	20	35	50+
Max.R for reliable values	50+	50+	50+	50+	44	18.5	18.5

SL (dB) when RL (dB) =

90	100	110	120	130	50	100	200	500	1000	2000	4000
185	195	205	215	225	50+?	22?	29?	50+?	50+?	50+?	50+?
180	190	200	210	220	50+?	20	26?	50+?	50+?	50+?	50+?
175	185	195	205	215	50+?	18	23?	50+?	50+?	50+?	47?
170	180	190	200	210	47?	16	20	50+?	45?	50+?	36?
165	175	185	195	205	38?	13	17	41?	32?	41?	27?
160	170	180	190	200	29?	11	14	31?	21?	30?	18?
155	165	175	185	195	20?	9.3	12	21?	13	19?	12
150	160	170	180	190	13?	7.3	9.1	13	7.1	11	6.8
145	155	165	175	185	8.2	5.5	6.7	7.9	3.7	6.3	3.7
140	150	160	170	180	4.3	3.8	4.6	4.1	1.8	3.3	1.9
135	145	155	165	175	2.3	2.4	2.8	2.1	.890	1.6	.917
130	140	150	160	170	.912	1.5	1.7	1.0	.427	.786	.440
125	135	145	155	165	.290	.762	.857	.488	.201	.376	.208
120	130	140	150	160	.091	.365	.428	.235	.094	.182	.097
115	125	135	145	155	.030	.119	.218	.091	.037	.083	.046
110	120	130	140	150	.017	.037	.072	.029	.012	.040	.020
105	115	125	135	145	.008	.012	.025	.009	.006	.016	.007
100	110	120	130	140	.005	.006	.008	.005	.003	.006	.00.4
?5	105	115	125	135	.003	.003	.005	.003	.002	.004	.002
90	100	110	120	130	.002	.002	.003	.002	-99	.002	.001

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' vs. source level and frequency for site SANDPIPER, based on various SIGNAL-TO-NOISE RATIO criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m) 15 (effective depth 35 m for 50 Hz)
Bottom Slope (-1 to 1) 0
Sound Speed (m/s) 1435
Max. Range (km) 50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	3	5	5	4	3	10	4
Sine (Crit.Ang.) (0-1)	.8	.8	.8	.8	.8	.8	.8
Bottom Refl. 'B' (0-5)	.04	.05	.15	.25	.3'5	.5	.5
Median Ambient (dB)	82	83	84	85	82	80	77
Max. R with Data (km)	10	20	20	20	20	20	15
Max.R for spher.spr.(km)	.01	.009	* 009	.009	.009	.009	.009
Max.R for cylin.spr.(km)	2	*7	*2	.1	.1	.07	.07
Max.R for multimode (km)	10	2.5	3	13	36..5	50+	50+
Max.R for reliable values	50+	50+	50+	50+	50+	44	44

SL (dB) when S:N (dB) =

0	10	20	30	40							
185	195	205	215	225	50+?	30?	36?	50+?	50+?	50+?	50+?
180	190	200	210	220	50+?	28?	33?	50+?	50+?	50+?	50+?
175	185	195	205	215	50+ ?	25?	29?	50+?	50+?	50+?	50+?
170	180	190	200	210	50+?	22?	26?	50+?	50+?	50+?	50+?
165	175	185	195	205	50+?	19	22?	50+?	50+?	50+?	50+?
160	170	180	190	200	44?	17	19	39?	50+?	50+?	50+?
155	165	175	185	195	34?	14	15	29?	42?	50+?	41?
150	160	170	180	190	25?	12	12	20	29?	50+?	31?
145	155	165	175	185	17?	9.3	9.1	13	17	36?	22?
140	150	160	170	180	11?	7.0	6.4	7.2	9.3	23?	14
135	145	155	165	175	6.4	4.9	4.0	3.8	4.8	14	8.5
130	140	150	160	170	3*3	3.1	2.5	1.9	2.4	7.4	4.7
125	135	145	155	165	1.8	1.9	1.3	.924	1.2	3.8	2.4
120	130	140	150	160	.577	1.0	.650	.445	.550	1.9	1.2
115	125	135	145	155	.186	.536	.319	.212	.263	.897	.575
110	120	130	140	150	.058	.176	.142	.085	.128	.427	.274
105	115	125	135	145	.025	.054	.044	.028	.044	.200	.134
100	110	120	130	140	.012	.020	.015	.009	.015	.093	.054
95	105	115	125	135	.006	.007	.006	.005	.006	.035	.020
90	100	110	120	130	.004	.004	.004	.003	.004	.011	.007

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence! vs. source level and frequency for site SANDPIPER,
based on various RECEIVED LEVEL criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m) 15 (effective depth 35 m for 50 Hz)
Bottom Slope (-1 to 1) 0
Sound Speed (m/s) 1435
Max. Range (km) 50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	3	5	5	4	3	10	4
Sine (Crit.Ang.) (0-1)	.8	.8	.8	.8	.8	.8	.8
Bottom Refl.'B'(0-5)	.04	.05	.15	.25	.35	.5	.5
Median Ambient (dB)	82	83	84	85	82	80	77
Max. R with Data (km)	10	20	20	20	20	20	15
Max.R for spher.spr. (km)	.01	.009	.009	.009	.009	.009	.009
Max.R for cylin.spr.(km)	2	.7	.2	.1	.1	.07	.07
Max.R for multimode (km)	10	2.5	3	13	36.5	50+	50+
Max.R for reliable values	50+	50+	50+	50+	50+	44	44

SL (dB) when RL (dB) =

90	100	110	120	130							
185	195	205	215	225	50+?	26?	32?	50+?	50+?	50+ ?	50+ ?
180	190	200	210	220	50+?	24?	28?	50+?	50+?	50+?	50+?
175	185	195	205	215	50+?	21?	25?	50+?	50+?	50+?	50+?
170	180	190	200	210	47?	18	21?	50+?	50+?	50+?	46?
165	175	185	195	205	38?	16	18	39?	49?	50+?	35?
160	170	180	190	200	29?	13	15	29?	35?	50+?	25?
155	165	175	185	195	20?	11	12	20	21?	36?	17?
150	160	170	180	190	13?	8.3	8.6	13	12	23?	11
145	155	165	175	185	8.2	6.1	5.9	7.2	6.3	14	6.0
140	150	160	170	180	4.3	4.1	3.6	3.8	3.2	7.4	3.2
135	145	155	165	175	2.3	2.6	2.2	1.9	1.5	3.8	1.6
130	140	150	160	170	.912	1.5	1.1	.924	.740	1.9	.772
125	135	145	155	165	.290	.784	.565	.445	.353	.897	.369
120	130	140	150	160	.091	.341	.279	.212	.172	.427	.178
115	125	135	145	155	.030	.109	.109	.085	.068	.200	.080
110	120	130	140	150	.017	.035	.035	.028	.024	.093	.028
105	115	125	135	145	.008	.011	.011	.009	.008	.035	.009
100	110	120	130	140	.005	.006	.006	.005	.005	.011	.005
95	105	115	125	135	.003	.003	.003	.003	.003	.006	.003
90	100	110	120	130	.002	.002	.002	.002	.002	.003	.002

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' vs. source level and frequency for site HAMMERHEAD, based on various SIGNAL-TO-NOISE RATIO criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m)	30
Bottom Slope (-1 to 1)	0
Sound Speed (m/s)	1435
Max. Range (km)	50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	0	4	-1	3	7	16	14
Sine (Crit.Ang.) (0-1)	.3	.3	.3	93	.3	.8	.8
Bottom Refl. 'B' (0-5)	.05	.09	.08	.14	.2	.8	1.2
Median Ambient (dB)	91	88	85	82	82	81	81
Max. R with Data (km)	10	20	20	20	20	15	10
Max.R for spher.spr. (km)	.03	.03	.03	.03	.03	.01	.01
Max.R for cylin.spr.(km)	5	5.5	6.5	3.5	2.5	.09	.05
Max.R for multimode (km)	0	11.5	50+	50+	50+	50+	50+
Max.R for reliable values	50+	50+	50+	50+	50+	27.5	18.5

SL (dB) when S:N (dB) =

0	10	20	30	40	50	100	200	500	1000	2000	4000
185	195	205	215	225	40?	50+?	50+?	50+?	50+?	50+?	50+?
180	190	200	210	220	35?	50+ ?	50+?	50+?	50+?	50+?	50+?
175	185	195	205	215	29?	50+?	50+?	50+?	50+?	50+ ?	50+?
170	180	190	200	210	24?	50+?	50+?	50+?	50+?	50+?	50+?
165	175	185	195	205	19?	44?	50+?	50+?	50+?	50+?	50+?
160	170	180	190	200	15?	34?	50+?	50+?	50+?	50+?	50+?
155	165	175	185	195	11?	24?	37?	'50+?	50+?	50+?	48?
150	16o	170	180	190	6.8	16	20	43?	50+?	50+?	37?
145	155	165	175	185	5.0	10	9.9	23?	31?	47?	27?
140	150	16o	170	180	1.6	5.8	5.0	12	17	31?	18?
135	145	155	165	175	.502	2.5	1.6	5.7	8*8	19?	11?
130	140	150	16o	170	.167	.796	.502	2.5	4.4	11	6.5
125	135	145	155	165	.050	.257	.167	.793	1.9	5.5	3.5
120	130	140	150	160	.029	.080	.050	.256	.628	2.7	1.8
115	125	135	145	155	.018	.037	.029	.080	.200	1.3	.848
110	120	130	140	150	.009	.023	.018	.037	.064	.626	.402
105	115	125	135	145	.005	.012	.009	.023	.032	.294	.191
100	110	120	130	140	.003	.006	.005	.012	.020	.145	.088
95	105	115	125	135	.002	.004	.003	.006	.010	.054	.034
90	100	110	120	130	-99	.002	.002	.004	.006	.023	.018

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' vs. source level and frequency for site HAMMERHEAD, based on various RECEIVED LEVEL criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m) 30
Bottom Slope (-1 to 1) 0
Sound Speed (m/s) 1435
Max. Range (km) 50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	0	4	-1	3	7	16	14
Sine (Crit.Ang.) (0-1)	.3	.3	.3	.3	.3	.8	.8
Bottom Refl. 'B' (0-5)	.05	.09	.08	.14	.2	.8	1.2
Median Ambient (dB)	91	88	85	82	82	81	81
Max. R with Data (km)	10	20	20	20	20	15	10
Max.R for spher.spr.(km)	.03	.03	.03	.03	.03	.01	.01
Max.R for cylin.spr.(km)	5	5.5	6.5	3.5	2.5	.09	.05
Max.R for multimode (km)	50+	11.5	50+	50+	50+	50+	50+
Max.R for reliable values	50+	50+	50+	50+	50+	27.5	18.5

SL (dB) when RL (dB) =

90	100	110	120	130	50	100	200	500	1000	2000	4000
185	195	205	215	225	41?	50+?	50+?	50+?	50+?	50+?	50+?
180	190	200	210	220	36?	50+?	50+?	50+?	50+?	50+?	50+?
175	185	195	205	215	30?	50+?	50+?	50+?	50+?	50+?	50+?
170	180	190	200	210	25?	50+?	50+?	50+?	50+?	50+?	50+?
165	175	185	195	205	20?	40?	50+?	50+?	50+?	50+?	50+?
160	170	180	190	200	16?	30?	37?	50+?	50+?	50+?	39?
155	165	175	185	195	11?	21?	20	30?	39?	50+?	29?
150	160	170	180	190	7.5	13	9.9	15	22?	34?	20?
145	155	165	175	185	5.2	7.9	5.0	7.6	12	21?	13?
140	150	160	170	180	2.0	5.0	1.6	3.7	5.8	12	7.3
135	145	155	165	175	.634	1.6	.502	1.3	2.8	6.3	4.0
130	140	150	160	170	.200	.502	.167	.398	.987	3.2	2.0
125	135	145	155	165	.064	.167	.050	.133	.317	1.5	.982
120	130	140	150	16o	.032	.050	.029	.046	.100	.727	.469
115	125	135	145	155	.020	.029	.018	.027	.041	.344	.223
110	120	130	140	150	.010	.018	.009	.016	.025	.167	.104
105	115	125	135	145	.006	.009	.005	.008	.014	.067	.043
100	110	120	130	140	.003	.005	.003	.005	.007	.026	.021
95	105	115	125	135	.002	.003	.002	.003	.004	.013	.009
90	100	110	120	130	-99	.002	-99	.002	.002	.006	.005

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' vs. source level and frequency for site CORONA, based on various SIGNAL-TO-NOISE RATIO criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m)	35
Bottom Slope (-1 to 1)	0
Sound Speed (m/s)	1435
Max. Range (km)	50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	0	2	1	5	5	15	9
Sine (Crit.Ang.) (0-1)	.2	.2	.3	.8	.8	.8	.8
Bottom Refl. 'B' (0-5)	.2	.3	.45	.85	.95	.95	1.0'5
Median Ambient (dB)	91	88	85	82	82	81	81
Max. R with Data (km)	20	30	30	30	30	20	20
Max.R for spher.spr. (km)	.07	.07	.05	.01	.01	.01	.01
Max.R for cylin.spr.(km)	2	4.5	1.3	.1	.09	.09	.07
Max.R for multimode (km)	0	5.5	14.5	48.5	50+	50+	50+
Max.R for reliable values	50+	50+	48.5	26	23	23	20

SL (dB) when S:N (dB) = 0	10	20	30	40	50	100	200	500	1000	2000	4000
185	195	205	215	225	17	43?	50+?	50+?	50+?	50+?	50+?
180	190	200	210	220	15	37?	50+?	50+?	50+?	50+?	50+?
175	185	195	205	215	13	31?	50+?	50+?	50+?	50+?	50+?
170	180	190	200	210	11	26	50+?	50+?	50+?	50+?	50+?
165	175	185	195	205	8.7	21	42?	50+?	50+?	50+?	50+?
160	170	180	190	200	6.9	16	30	50+?	50+?	50+?	48?
155	165	175	185	195	5.1	12	19	49?	46?	50+?	37?
150	160	170	180	190	3.5	7*5	12	28?	27?	50+?	27?
145	155	165	175	185	2.3	4.9	6.5	15	15	41?	18
140	150	160	170	180	.907	2.9	3.3	7.9	7.8	27?	11
135	145	155	165	175	.289	.907	1.6	3.9	3.9	16	6.5
130	140	150	160	170	.091	.289	.683	1.9	1.9	8.6	3.5
125	135	145	155	165	.050	.091	.219	.897	.881	4.4	1.8
120	130	140	150	160	.029	.050	.069	.426	.415	2.2	.844
115	125	135	145	155	.018	.029	.037	.199	.195	1.0	.400
110	120	130	140	150	.009	.018	.023	.091	.091	.485	.191
105	115	125	135	145	.005	.009	.012	.030	.030	.230	.087
100	110	120	130	140	.003	.005	.006	.017	.017	.108	.030
95	105	115	125	135	.002	.003	.004	.008	.008	.037	.017
90	100	110	120	130	-99	.002	.002	.005	.005	.020	.008

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' vs. source level and frequency for site CORONA, based on various RECEIVED LEVEL criteria.
Bottom slope O (i.e. propagation to east or west) is assumed.

Water Depth (m) 35
Bottom Slope (-1 to 1) 0
Sound Speed (m/s) 1435
Max. Range (km) 50

Frequency (Hz)	50	1,00	200	500	1000	2000	4000
Local Anomaly (dB)	0	2	1	5	5	15	9
Sine (Crit.Ang.) (0-1)	.2	.2	.3	.8	.8	.8	.8
Bottom Refl. 'B' (0-5)	.2	.3	.45	.85	.95	.95	1.05
Median Ambient (dB)	91	88	85	82	82	81	81
Max. R with Data (km)	20	30	30	30	30	20	20
Max.R for spher.spr. (km)	.07	.07	.05	.01	.01	.01	.01
Max.R for cylin.spr.(km)	2	4.5	1.3	.1	.09	.09	.07
Max.R for multimode (km)	50+	5.5	14.	48.5	50+	50+	50+
Max.R for reliable values	50+	50+	48.5	26	23	23	20

SL (dB) when RL (dB) =

90	100	110	120	130	50	100	200	500	1000	2000	4000
185	195	205	215	225	17	40?	50+?	50+?	50+?	50+?	50+?
180	190	200	210	220	15	35?	50+?	50+?	50+?	50+?	50+?
175	185	195	205	215	13	29	50+?	50+?	50+?	50+?	50+?
170	180	190	200	210	11	24	42?	50+?	50+?	50+?	50+?
165	175	185	195	205	9.1	19	30	50+?	50+?	50+?	39?
160	170	180	190	200	7.2	14	19	35?	34?	50+?	29?
155	165	175	185	195	5.4	9.9	12	20	19	45?	20
150	160	170	180	190	3.8	6. l	6.5	10	10	29?	13
145	155	165	175	185	2.4	4.6	3.3	5.2	5.1	18	7.3
140	150	160	170	180	1.1	1.8	1.6	2.5	2.5	9.7	4.0
135	145	155	165	175	.365	.574	.683	1.2	1.2	5.0	2.0
130	140	150	16o	170	.119	.186	.219	.574	.562	2.5	.978
125	135	145	155	165	.057	.071	.069	.273	.267	1.2	.467
120	130	140	150	160	.032	.041	.037	.134	.129	.564	.221
115	125	135	145	155	.020	.025	.023	.046	.046	.268	.103
110	120	130	140	150	.010	.014	.012	.022	.022	.13	.037
105	115	125	135	145	.006	.007	.006	.010	.010	.046	.020
100	110	120	130	140	.003	.004	.004	.006	.006	.022	.009
95	105	115	125	135	.002	.002	.002	.003	.003	.010	.005
90	100	110	120	130	-99	.001	.001	.002	.002	.006	.003

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence vs. source level and frequency for site ERIK,
based on various SIGNAL-TO-NOISE RATIO criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m) 40
Bottom Slope (-1 to 1) 0
Sound Speed (m/s) 1435
Max. Range (km) 50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	0	-2	-1	-1	-3	-1	-5
Sine (Crit.Ang.) (0-1)	.8	.8	.3	.3	.3	.3	.3
Bottom Refl. 'B' (0-5)	.08	.15	.2	.4	.55	.55	.6
Median Ambient (dB)	91	88	85	82	82	81	81
Max. R with Data (km)	20	40	40	40	40	40	20
Max.R for spher.spr. (km)	.01	.01	.05	.05	.05	.05	.05
Max.R for cylin.spr.(km)	1.2	.6	3	1.5	1.2	1.2	1.1
Max.R for multimode (km)	7.5	16.5	48.5	50+		50+	
Max.R for reliable values	50+	50+	50+	50+	39.5 50+	39.5	36.5 50+

SL (dB) when S:N (dB) =

0	10	20	30	40	50	100	200	500	1000	2000	4000
185	195	205	215	225	50+?	50+?	50+?	50+?	50+?	50+?	50+?
180	190	200	210	220	45?	50+?	50+?	50+?	50+?	50+?	50+?
175	185	195	205	215	37?	50+?	50+?	50+?	50+?	50+?	50+?
170	180	190	200	210	30?	48?	50+?	50+?	50+?	50+?	41?
165	175	185	195	205	23?	34	50+?	50+?	50+?	50+?	31?
160	170	180	190	200	17	23	48?	50+?	39	42?	21?
155	165	175	185	195	11	14	26	34	22	27	14
150	160	170	180	190	7.0	7.7	14	18	12	16	8.2
145	155	165	175	185	3.8	3.9	6.8	8.8	5.9	8.5	4.5
140	150	160	170	180	1.9	1.9	3.4	4.3	2.9	4..4	2.3
135	145	155	165	175	1.0	.934	1.2	2.0	1.4	2.1	
130	140	150	160	170	.320	.400	.379	.750	.473	.921	. x
125	135	145	155	165	.101	.134	.125	.242	.158	.297	.124
120	130	140	150	160	.032	.041	.050	.076	.058	.094	.050
115	125	135	145	155	.019	.021	.029	.041	.032	.046	.029
110	120	130	140	150	.009	.010	.018	.025	.020	.027	.018
105	115	125	135	145	.005	.006	.009	.014	.010	.016	.009
100	110	120	130	140	.003	.003	.005	.007	.006	.008	.005
95	105	115	125	135	.002	.002	.003	.004	.003	.005	.003
90	100	110	120	130	-99	-99	.002	.002	.002	.003	.002

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' vs. source level and frequency for site ERIK,
based on various RECEIVED LEVEL criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m) 40
Bottom Slope (-1 to 1) 0
Sound Speed (m/s) 1435
Max. Range (km) 50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	0	-2	-1	-1	-3	-1	-5
Sine (Crit.Ang.) (0-1) "	.8	.8	.3	.3	.3	.3	.3
Bottom Refl. 'B' (0-5)	.08	.15	.2	.4	.55	.55	.6
Median Ambient (dB)	91	88	85	82	82	81	81
Max. R with Data (km)	20	40	40	40	40	40	20
Max.R for spher.spr. (km)	.01	.01	.05	.05	.05	.05	.05
Max.R for cylin.spr.(km)	1.2	.6	3	1.5	1.2	1.2	1.1
Max.R for multimode (km)	7.5	16.5	48.5	50+		50+	50+
Max.R for reliable values	50+	50+	50+	50+	39.5 50+	39.5	36.5

SL (dB) when RL (dB) =

90	100	110	120	130							
185	195	205	215	225	50+?	50+?	50+?	50+?	50+?	50+?	50+?
180	190	200	210	220	46?	50+?	50+?	50+?	50+?	50+?	44?
175	185	195	205	215	39?	50+?	50+?	50+?	50+?	50+?	33?
170	180	190	200	210	31?	42?	50+?	50+?	48?	45?	23?
165	175	185	195	205	24?	29	48?	43?	28	29	15
160	170	180	190	200	18	18	26	23	15	18	9.2
155	165	175	185	195	12	11	14	12	7.9	9.7	5.1
150	16o	170	180	190	7.6	5.9	6.8	5.7	3.9	5.0	2.6
145	155	165	175	185	4.3	3.0	3.4	2.8	1.9	2.5	1.3
140	150	160	170	180	2.2	1.4	1.2	1.2	.745	1.2	.463
135	145	155	165	175	1.2	.696	.379	.378	.242	.375	.157
130	140	150	160	170	.400	.257	.125	.125	.076	.125	.057
125	135	145	155	165	.134	.080	.050	.050	.041	.050	.032
120	130	140	150	160	.041	.028.	.029	.029	.025	.029	.020
115	125	135	145	155	.021	.017	.018	.018	.014	.018	.010
110	120	130	140	150	.010	.008	.009	.009	.007	.009	.006
105	115	125	135	145	.006	.005	.005	.005	.004	.005	.003
100	110	120	130	140	.003	.003	.003	.003	.002	.003	.002
95	105	115	125	135	.002	.002	.002	.002	.001	.002	-99
90	100	110	120	130	-99	-99	-99	-99	-99	-99	-99

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' **vs. source level and frequency** for site BELCHER,
based on various SIGNAL-TO-NOISE RATIO criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m)	55
Bottom Slope (-1 to 1)	0
Sound Speed (m/s)	1435
Max. Range (km)	50

Frequency (Hz)	**50**	**100**	**200**	**500**	**1000**	**2000**	**4000**
Local Anomaly (dB)	5	5	3	3	-2	0	-8
Sine (Crit.Ang.) (0-1)	.8	.8	.3	.2	.3	.4	.3
Bottom Refl. 'B' (0-5)	.2	.3	.2	.25	*35	.4	.5
Median Ambient (dB)	91	88	85	82	82	81	81
Max. R with Data (km)	20	**50**	**50**	**50**	**50**	**40**	**10**
Max.R for spher.spr.(km)	.03	.03	.09	.1	.09	.05	.09
Max.R for cylin.spr.(km)	.6	.4	4.5	8.5	2.5	1.3	1.5
Max.R for multimode (km)	8	21.5	50+	50+	50+	50+	50+
Max.R for reliable values	**50+**	**50+**	**50+**	**50+**	**50+**	50+	44

SL (dB) when S:N (dB) = 0	10	20	30	40							
185	195	205	215	225	50+?	50+	50+	**50+**	50+	50+?	50+?
180	190	200	210	220	50+?	50+	**50+**	50+	50+	50+?	50+?
175	185	195	205	215	**42?**	**50+**	**50+**	**50+**	50+	50+?	46?
170	180	190	200	210	34?	**50+**	**50+**	50+	50+	50+?	34?
165	175	185	195	205	**27?**	**50+**	**50+**	**50+**	50+	50+?	25?
160	170	180	190	200	**20**	**38**	50+	50+	47	46?	16?
155	165	175	185	195	**14**	**24**	**46**	50+	27	30	9.9
150	160	170	180	190	**8.5**	**15**	**24**	**33**	14	18	5.6
145	155	165	175	185	**5.1**	**7.7**	12	**17**	7.3	9.8	2.9
140	150	160	170	180	**2.6**	**3.9**	5.6	**8.6**	3.5	5.0	1.3
135	145	155	165	175	1.3	1.9	2.2	2.9		2.5	.425
130	140	150	160	170	.659	.916	.688	.911	.:52	1.1	.144
125	135	145	155	165	**.236**	**.440**	.221	**.291**	.145	.365	.064
120	130	140	150	160	**.073**	**.154**	**.080**	**.123**	.064	.120	.037
115	125	135	145	155	**.029**	**.047**	**.046**	**.064**	.037	.050	.023
110	**120**	**130**	**140**	**150**	**.018**	**.025**	**.027**	**.037**	.023	.029	.012
105	**115**	**125**	**135**	145	**.009**	**.014**	**.016**	**.023**	.012	.018	.006
100	**110**	**120**	**130**	**140**	**.005**	**.007**	**.008**	**.012**	.006	.009	.004
95	105	115	125	135	**.003**	**.004**	**.005**	**.006**	.004	.005	.002
90	**100**	**110**	**120**	**130**	**.002**	**.002**	**.003**	**.004**	.002	.003	.001

? Range is uncertain; it exceeds the maximum range for which model is reliable.

'Zone of influence' vs. source level and frequency for site BELCHER,
based on various RECEIVED LEVEL criteria.
Bottom slope 0 (i.e. propagation to east or west) is assumed.

Water Depth (m)	55
Bottom Slope (-1 to 1)	0
Sound Speed (m/s)	1435
Max. Range (km)	50

Frequency (Hz)	50	100	200	500	1000	2000	4000
Local Anomaly (dB)	5	5	3	3	-2	0	-8
Sine (Crit.Ang.) (0-1)	.8	.8	.3	.2	.3	.4	.3
Bottom Refl. 'B' (0-5)	.2	.3	.2	.25	.35	.4	.5
Median Ambient (dB)	91	88	85	82	82	81	81
Max. R with Data (km)	20	50	50	50	50	40	10
Max.R for spher.spr. (km)	.03	.03	.09	.1	.09	.05	.09
Max.R for cylin.spr.(km)	.6	.4	4.5	8.5	2.5	1.3	1.5
Max.R for multimode (km)	8	21.5	50+	50+	50+	50+	50+
Max.R for reliable values	50+	50+	50+	50+	50+	50+	44

SL (dB) when RL (dB) =

90	100	110	120	130							
185	195	205	215	225	50+?	50+	50+	50+	50+	50+?	48?
180	190	200	210	220	50+?	50+	50+	50+	50+	50+?	37?
175	185	195	205.	215	43?	50+	50+	50+	50+	50+?	26?
170	180	190	200	210	36?	50+	50+	50+	50+	50+?	18?
165	175	185	195	205	28?	48	50+	50+	34	33	11?
160	170	180	190	200	21?	32	46	43	19	20	6.3
155	165	175	185	195	15	21	24	22	9.6	11	3.3
150	160	170	180	190	9.4	12	12	11	4.7	5.8	1.6
145	155	165	175	185	5.7	5.9	5.6	4.5	2.1	2.9	.530
140	150	160	170	180	3.0	2.9	2.2	1.4	.682	1.4	.177
135	145	155	165	175	1.5	1.4	.688	.460	.220	.456	.071
130	140	150	160	170	.745	.682	.221	.168	.080	.153	.041
125	135	145	155	165	.292	.292	.080	.080	.046	.057	.025
120	130	140	150	160	.092	.092	.046	.046	.027	.032	.014
115	125	135	145	155	.033	.033	.027	.027	.016	.020	.007
110	120	130	140	150	.020	.020	.016	.016	.008	.010	.004
105	115	125	135	145	.010	.010	.008	.008	.005	.006	.002
100	110	120	130	140	.006	.006	.005	.005	.003	.003	.001
95	105	115	125	135	.003	.003	.003	.003	.002	.002	-99
90	100	110	120	130	.002	.002	.002	.002	-99	-99	-99

? Range is uncertain; it exceeds the maximum range for which model is reliable.

APPENDIX F

ONE-THIRD OCTAVE BAND FREQUENCY ALLOCATIONS

APPENDIX F: ONE-THIRD OCTAVE BAND FREQUENCY ALLOCATIONS.

These one-third octave band frequency allocations are provided to assist the reader in interpretation of Figures 20, 22, 23, 24, 25, 28, and 29.

Band No.	Frequency (Hz)
5	3.15
6	4.0
7	5.0
8	6.3
9	8.0
10	10.0
11	12.5
12	16.0
13	20.0
14	25.0
15	31.5
16	40
17	50
18	63
19	80
20	100
21	125
22	160
23	200

Band No.	Frequency (Hz)
24	250
25	315
26	400
27	500
28	630
29	800
30	1000
31	1250
32	1600
33	2000
34	2500
35	3150
36	4000
37	5000
38	6300
39	8000
40	10000
41	12500
42	16000
43	20000